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VISUAL SEARCH WITH COLOR

Robert Charles Carter, jr.

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VISUAL SEARCH WITH COLOR

Robert Charles Carter, Jr

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Several experiments were conducted to discover how rapidly people can find a particular target when they know the color of the target. More than 14,000 searches were conducted by 212 subjects. The subjects searched for a specific colored three-digit number among other colored three-digit numbers on a circular display screen which subtended about 14 degrees of visual angle. Three factors had a profound effect on search speed. Search time increased dramatically (and approximately linearly) as the number of display items of

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the target's color increased from one to the display density. Search time also increased when the number of display items of different colors from the target increased if the color of these items was sufficiently similar to that of the target. If the color of these background items was dissimilar to that of the target, then the background items had no effect on search time. A color difference calculation was shown to be moderately related to the apparent similarity of colors. An effect of patterned versus random placement of the target-colored items was also demonstrated. There was no consistent effect on search time of target placement, the number of items adjoining the target, or practice of the search task. None of the individual difference variables studied (parafoveal acuity, foveal acuity, stereo acuity, reading speed, age, sex, recent drug or alcohol use, smoking habits, nor color vision) were significantly related to differences of search speed. The results were also cast in the form of a cumulative distribution function (CDF) of search time for each of 17 search conditions. The CDF's were well described by an exponential probability curve which included a delay for orientation and response of the subjects to the display.

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ABSTRACT

Several experiments were conducted to discover how rapidly people can find a particular target when they know the color of the target. More than 14,000 searches were conducted by 212 subjects. The subjects searched for a specific colored three-digit number among other colored three-digit numbers on a circular display screen which subtended about 14 degrees of visual angle. Three factors had a profound effect on search speed. Search time increased dramatically (and approximately linearly) as the number of display items of the target's color increased from one to the display density. Search time also increased when the number of display items of different colors from the target increased if the color of these items was sufficiently similar to that of the target. If the color of these background items was dissimilar to that of the target, then the background items had no effect on search time. A color difference calculation was shown to be moderately related to the apparent similarity of colors. An effect of patterned versus random placement of the target-colored items was also demonstrated. There was no consistent effect on search time of target placement, the number of items adjoining the target, or practice of the search task. None of the individual difference variables studied (parafoveal acuity, foveal acuity, stereo acuity, reading speed, age, sex, recent drug or alcohol use, smoking habits, nor color vision) were significantly related to differences of search speed. The results were also cast

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CHAPTER 1

LITERATURE REVIEW AND INTRODUCTION

This is a report of an investigation of how rapidly a person can find something he is looking for. People searched for colored three-digit numbers in this research. Search time for such targets has previously been shown to be related to some characteristics of the target's context and of the person doing the searching. Specifically, the relevant characteristics of the context are: the number of items in the field of view (display density), the number of items that share the target's color (Target Class Size, or TCS), the number of background items not sharing the target's color (density minus TCS), the proximity of the background items to the target, the visual eccentricity of the target and associated background items, similarity of the background and target class items, and the position of the target on a visual display. Individual characteristics which have been associated with search time include acuity in parafoveal vision, reading speed, and smoking habits. These previous findings will be reviewed, and a series of experiments which extends these findings will be described.

Variables Affecting Search of Abstract Information Displays

Display Density and Target Class Size

An early experiment with the search task (Green, McGill, & Jenkins, 1953) showed that search time is proportional to the number of alternatives to the target within the display. This number has come to be called display density (Smith, 1962). Green et al. also suggested that color could be used to separate categories of displayed objects.

Green and Anderson (1956), in a follow-up to the experiment of Green, McGill, and Jenkins, confirmed that search time increases in proportion to display density. They also found that if the target is color coded and the observer knows the target's color, then search time is proportional to the number of display items of the same color as the target. It seems that when color coding is used, search is limited to target-colored items. (The number of items coded the same way as the target does not have a specific name in the literature, but it will be called Target Class Size (TCS) in this discussion.) Green and Anderson also found that an observer takes slightly more time to search for a target on a multicolor display with a particular TCS than he takes to find a target on a monochrome display with a density equal to that TCS. Furthermore, they found that if the target's color is unknown, displays on which one color predominates are easier to search than are displays on which various colors are equally represented. As an extreme case of this phenomenon, Green and Anderson found that a monochromatic display can be searched faster than a multicolor display.

Smith (1962) found that search time increased approximately linearly with display density and that search time on multicolor display was considerably reduced if the color of the target was known. Smith did not confirm Green and Anderson's (1956) finding of inferiority of multicolor displays compared with monochromatic displays when the target's color is unknown. His experiment was similar to theirs, using numbers which were coded with color in a partially redundant fashion. Smith attributed the difference between his results and Green and Anderson's to different display projection techniques. Smith used rear projection which enabled him to maintain brighter ambient lighting than Green and Anderson had with their forward projected displays. Smith speculated that when ambient lighting is bright enough so that the observers can see the plane of the display screen, multicolor and monochromatic displays would give similar results for a display user who was unaware of the target's color. Smith believed that Green and Anderson's results reflected chromostereopsis which distracted users of multicolor displays who did not know the color of the target. In any event, Smith showed that the problem is obviated by the presence of a reference plane produced by an apparent display screen.

Smith's search times were not affected by whether the display had a black or a white background, nor were they affected by the choice of target color or the other colors used on the displays. Search time was shown by Smith to be proportional to density for densities of 20, 40, 60, 80, and 100 on displays coded with as many as five colors. However, density was confounded with TCS in Smith's experiment because

display items were always equally divided among the available colors. This means that density and the number of colors used were highly correlated with TCS. When TCS was held constant while density and the number of colors increased in unison, search time was essentially constant but increased slightly (1.2 seconds). Smith explained this slight increase as the time taken to notice wrong-colored items before ignoring them and attending only to target-colored items.

Smith wrote in 1971,

> a variable that I always wished I had time to investigate but didn't, at least not to my own satisfaction, is the question of the proportion of target class items to non-targets. If the target is known to be red, say, can you determine the usefulness of this information in a search task as the number of red items displayed varies from just one to 100 percent?

In essence, he was asking what is the effect of TCS when it is varied from its minimum possible value of one to its maximum value, the display density.

Green and Anderson (1956) varied TCS from 10 to 60 on a display with density of 60. Their finding that search time is proportional to TCS suggests that search time would be as small as possible if the target had a unique color. In support of this notion is the finding by Carter and Cahill (1979) that search time remained proportional to TCS as TCS approached one.

In contrast to this evidence for a linear relation between search time and TCS, Schontz, Trumm, and Williams (1971) suggested that there is an optimum value for TCS which minimizes search time. Similarly, Gordon and Winwood (1973) depicted search time leveling off as display density becomes less than 10 on black-and-white displays.

These results suggest a deviation from the linear TCS-search time relationship when TCS is less than 10.

In summary, an experiment is needed in which the subjects search for a color-coded target on displays with TCS ranging from one to the display density. Density should also be varied to test the generality of Green and Anderson's results obtained with a single density.

Background Objects

All of the objects on a display are either in the target class or are background items. The effect on search performance of objects in the target class has already been recounted. Now the effects of background objects will be discussed. Most of the evidence on background objects comes from tachistoscopic research, where they are called "visual noise." This term for background objects is attributed by Eriksen (1955) to French (1954), and it implies a visual analogy to auditory noise which interferes with perception of auditory messages. The terms "background objects" and "visual noise" will be used interchangeably in this discussion.

The tachistoscopic literature is relevant to visual search because each fixation in a visual search is analogous to a tachistoscopic presentation of 200 - 350 msec, separated from the next fixation by a period of inhibited vision associated with the saccades which punctuate the fixations (Volkmann, 1976). Evidence for this claim is provided by Eriksen and Spencer (1969). They varied the rate of presentation from one scene every 5 msec to one scene every 3 seconds.

but even this extreme variation of presentation rate had no effect on target detection performance. There was also no effect of the position of the target in the sequence of scenes. Furthermore, Lamar (1960) states that "any description of an operational search situation must be built up out of what happens during each fixation" (p. 1). Phenomena which have been shown to accrue in a tachistoscopic situation may be presumed to apply also to search fixations which are of approximately the same duration.

It has been established (e.g., Bjork & Murray, 1977) that visual noise delays responses to targets and reduces accuracy of perception of targets. The most important characteristics of visual noise are: (1) proximity to the target, (2) eccentricity of the noise-target ensemble, (3) the number of noise elements, (4) stimulus similarity of the target and noise, (5) response similarity of the target and noise, and (6) the prägnanz of the noise and target. These characteristics and their effects will be discussed in detail.

Proximity. Proximity to the target is necessary for visual noise to affect perception of the target. It is a common experience that objects which are too far from the line of regard have little conscious effect. Williams (1949) has shown that stimuli must be within a degree or two of the line of sight for any very exact information about them to be available to the subject. It is reasonable to expect that noise must also be within this radius of the line of sight if it is to have an effect. Eriksen and Hoffman (1972) found that the presence of noise letters interfered with perception of target letters only when the noise was less than 1° from the target

(the scenes lasted one second). Similarly, tachistoscopic targets arranged at the vertices of an imaginary square have uncorrelated reporting errors when they are all at least 1° from each other, but reporting errors for targets become correlated when the targets are within 1° of each other (Collins & Eriksen, 1967). Townsend, Taylor, and Brown (1971) found that a blank space in a string of letters makes the following letter more recognizable, even when viewing time is unlimited. With 40-msec exposures, Strangert and Brannstrom (1975) found that reaction times increased drastically when randomly chosen letters were placed within .43° of the target letter. Eriksen and Eriksen (1974) showed that visual noise within 1° of the target letter increases errors and latency of responses to targets which are always presented at the same location on a display exposed for one second. Bjork and Murray (1977) obtained the same results as Eriksen and Eriksen by exposing targets for 50 msec and inquiring about what letter was in a particular position of an array of letters, shapes, and blanks. In general, then, the presence of visible objects within about 1° of a visual target impairs the speed and accuracy of responses to the target.

Eccentricity of the Noise-Target Ensemble. The target and adjoining visual noise may be in the line of sight (foveal), or out of the line of sight (parafoveal). Of course, performance is poorer in parafoveal vision, but it is not clear what effect visual noise would have in parafoveal vision. To answer this question, Taylor and Brown (1972) presented a string of as many as nine letters immediately to the right of a fixation point, and allowed unlimited

viewing time. Subjects were asked to read the letters while maintaining fixation on the fixation point. It was found that letters which had other letters on each side were read less accurately than letters with only one letter neighboring them, and letters presented in isolation were read most accurately. These differences were accentuated by the eccentricity (out to 3°) of the target letter. Reading accuracy was 50% lower for letters with neighbors at 3° eccentricity than for a letter in isolation at 3°. An innovative twist in this experiment was that the letter strings were presented monocularly, binocularly, or dichoptically. The dichoptic case is most interesting because the same effect of visual noise was found whether the left and right eyes saw "ANOQ" and "BCDV" or "A O B D" and "N Q C V." In either case, the scene would be perceived as "ANOQBCDV" but the retinae of the eyes were presented with spaced stimuli in one case and grouped stimuli in the other case. Because the spacing should have somewhat mitigated the effects of retinal inhibition of neighboring letters, Taylor and Brown concluded that the effect of visual noise must be, at least in part, post-retinal. Wolford and Hollingsworth (1974) also had subjects view and report strings of 9 letters, but their presentations lasted 200 msec, and the strings were presented either to the left or right of the fixation point. They found that the effect of neighboring letters increased at greater eccentricity in either the left or right visual field.

In another experiment demonstrating the effect of eccentricity and noise, Strangert and Brannstrom (1975) presented a horizontal

pair of letters for 40 msec, and the subject's task was to indicate which of the two letters matched a probe letter presented after the pair. The pairs of letters were presented 2.27° or 3.27° in the left or right visual field, and other letters were placed .06°, .43°, .8°, or several degrees from the target pair. Both errors and reaction time increased with eccentricity, but the effect of eccentricity was multiplied by the presence of noise letters within .43° of the target pair. This effect was referred to as "tunnel" vision by Norman Mackworth (1965) who discovered the interaction of eccentricity and visual noise. He hypothesizes (1976) that the useful field of view constricts to hold only as much information as can be processed by a limited system for visual perception. This is in contrast to Eriksen's theory that there is a 1° field of view and that performance is degraded throughout that visual angle when noise is present. Although Mackworth's hypothesis is more complicated, it seems to be supported by the ability of subjects to respond to cues outside of 1° of the line of sight. Eriksen handles this problem by inventing a mobile spot of attention which can rove from the line of sight (Colegate, Hoffman, & Eriksen, 1973; Eriksen & Hoffman, 1972). The difference between these theories becomes untestable as the spot of attention is allowed to move with great speed. In any case, it is clear that estimates of what a subject can see which are based on measurements of peripheral acuity without noise will be gross overestimates of what can be seen in the presence of visual noise. Engel (1977) has most recently demonstrated narrowing of the field of view by visual noise and its effect on search time.

<u>The Number of Noise Elements</u>. The number of noise elements on a display has at least two effects on a search task. First, when there are more elements on the display, more fixations are included in the search, and search time increases proportionately (Gould & Dill, 1969; Snyder & Taylor, 1976). Second, the number of noise elements in the vicinity of the target decreases the perceptibility of the target. Indeed, Mackworth and Mackworth (1958) showed that a person will sometimes look directly at the target of a search task without terminating the search--"looking is not always seeing" (pp. 439, 444). These two effects increase the total number of fixations required to complete the search and decrease the effectiveness of each fixation.

Monk and Brown (1975) suggested that the classic increase of search time with the number of items on a display (e.g., Cahill & Carter, 1976; Gordon & Winwood, 1973; Green & Anderson, 1956; Green, McGill, & Jenkins, 1953; Smith, 1962) is really an artifact of the number of items in the vicinity of the target. The number of items in the vicinity of a target would be expected to increase as the total number of items on the display increases. In their experiment, Monk and Brown used double dots as search targets on a field of single dots which constituted visual noise. They showed that search time increased in proportion to the number (0 - 8) of noise dots adjoining the target. None of the investigations demonstrating an effect of the total number of items has controlled the number of items in the vicinity of the target. Monk and Brown's hypothesis is eminently testable, but has not yet been tested.

Additional evidence for the effect of the number of noise elements comes from Eriksen (1955) who found that search time increased linearly with the number of noise elements on a display. Colegate, Hoffman, and Eriksen (1973) showed that verbal reaction time for identification of a target letter on a 2° display was faster with 7 noise letters on the display than when there were 11 noise letters. Eye movements were precluded by 100-msec presentation, and the absence of eye movements was checked with an electro-oculogram.

Another kind of visual noise is grid lines on displays and edges of displays. Reilly and Teichner (1962) found that the proportion of targets detected in up to 9 seconds decreased as the number of grid lines on a display increased beyond one. Similarly, Eriksen (1955) showed that the time required to locate 10 targets increased as the number of square partitions of the display increased.

Visual Similarity of the Target and Noise. Similarity is an elusive concept. Visual similarity is the degree to which one thing looks like another. However, this definition tells us little about how we measure or produce this "degree," and, as Bridgman (1955) has observed, knowing the operations by which we measure or produce a concept is a necessary condition for understanding the concept. The most common method for measuring visual similarity is to determine the frequency of identification reversals. For example, Kinney (1965) has listed certain letters which are often mistaken for each other, presumably because the letters are visually similar. Snyder and

Maddox (1978) have tabulated the frequency of mistaking any letter for any other letter (a 26 x 26 matrix) in each of several fonts. Similar tabulations of auditory similarity of letter sounds have been compiled by Conrad (1964). In general, an n-by-n "confusion matrix" can be generated for any set of n sensory entities. The similarity of any two of the entities is a monotonically increasing function of the frequency of mistaking one item for the other; the more frequent the mistakes, the more similar the items.

Williams (1967a) applied this method to measure the similarity of various sizes, shapes, colors, and lightnesses, and their combinations in peripheral vision. On the basis of these data, Williams (1973) contends that when objects differ in more than one aspect, similarity is governed by the most salient perceptual dimension they share. For example, if items differ in color and shape, their similarity in peripheral vision will be determined predominantly by color. Although Williams' data are the most extensive developed on this topic, his conclusion about similarity of multidimensional objects is generally supported by the earlier findings of Eriksen (1952) and Eriksen and Hake (1955).

Knowing that particular pairs of objects occasionally will be mistaken for each other is useful only when the number of pairs of objects is relatively small (e.g., letters or numerals). A more general measure of similarity would be based upon the shared characteristics of any pair of objects which will lead to mistaken recognition. For instance, E. J. Gibson (1965) and Gibson, Osser, Schiff, and Smith (1964) developed a method for predicting the

frequency of mistaken identifications of letters which is based on the number of features that are shared by the letters. Likewise, Bloomfield (1972, 1973), Engel (1977), and Williams (1966a, 1967a, 1967b) show that when size coding is used the frequency of mistaking a background item for a target depends on the difference between the size of the target and the size of the background item. Williams (1967a) also found that when targets are specified in terms of color, similarity of objects depends on the difference of their hue, value, or chroma. Williams did not combine these three aspects of color into a single index of color difference analogous to the obvious index of size difference. However, indices of color difference are now available (Judd & Wyszecki, 1975), and their relation to Williams' data on color similarity (the frequency of confusing one color for another) should be tested!

Similarity of background to target objects results in an increase in the number of fixations on background objects (Gould & Dill, 1969; Williams, 1967a) and an increase in the duration of fixations on both targets and background objects. Because approximately 90 percent of search time is composed of fixations (Gould, 1969, cited in Snyder & Taylor, 1976), an increase of the number and duration of fixations increases search time appreciably. Furthermore, Gould and Dill (1969) noted that observers rarely refix targets, regardless of target-background similarity. However, the frequency of multiple fixations of the same background object increased with target-background similarity.

In a tachistoscopic demonstration of the effects of the similarity of targets and backgrounds, Gardner (1973) asked subjects to view 10-msec presentations of 2, 3, 4, or 5 items including a target which was either T or F, and similar or dissimilar background items. The dissimilar background consisted of O's and the similar background consisted of a hybrid figure composed of elements of both T and F. The subject's task was to say whether T or F or neither had been presented. The results were quite different when the two types of background were used. With the dissimilar background, the absence of a target was detected with near-perfect accuracy, and the presence of targets was identified with 85% accuracy irrespective of the number (1 - 4) of background items. With the similar background, performance declined as more background items were added. Performance started at 75% detection of targets and 55% detection of the absence of a target when there was one background item. When there were four similar background items, accuracy of detecting targets or their absence declined to 4%. Jonides and Gleitman (1972) used letters as targets, and other letters as a similar background and numbers as a dissimilar background for 150-msec presentations. They measured the latency of responses rather than accuracy and found the same similarity-by-number of background items interaction that Gardner (1973) did. In contrast, the interaction was not detected in an experiment by McIntyre, Fox, and Neale (1970). They measured accuracy of detecting target letters (T or F) during a 90-msec presentation of an 8-, 12-, or 14-letter array. However, both McIntyre et al. and Jonides and Gleitman found that

performance declined when background items were made more similar to the target.

In order to demonstrate the effects of similar and dissimilar noise, Estes (1972) displayed strings of 4, 6, or 8 letters for 100 msec. The subjects were to respond by pressing one button if A, B, C, or D appeared in the string or another button if S, T, U, or V appeared. In addition to a target letter, the string contained similar noise (other letters) or dissimilar noise (dot arrays of the same size as letters). He found that both reaction time and detection performance were superior with dissimilar noise. In addition, he found that the effect of proximity of noise to the target increased with eccentricity for similar noise but not for dissimilar noise. This result suggests that the inhibition of targets by noise has a biologically adaptive function; something that is similar to its background will be inhibited, but something that is different from the background is not inhibited. This mechanism is sensitive to unusual or informative objects in the background (Reicher, Snyder, and Richards, 1976).

Kaplan, Yonas, and Shurcliff (1966) conducted a clever experiment to determine whether visual information is given an acoustic code for cognitive processing, or whether the information retains its visual characteristics. They used a search task with 30 lines of 4 letters per line, and measured search time. The targets were E or K, and they were searched in the context of letters chosen to be acoustically similar to E and K or visually similar to E and K. Visual similarity accounted for 25% of the variance in the experiment,

and acoustic similarity accounted for only .3%. The phenomenon of visual coding was upheld, and similarity of the background to the targets impeded search. An interesting point is that a visual E and an acoustic E are really different stimuli, so one must specify the stimulus carefully if the similarity ratings are to be meaningful. The importance of specifying exactly what constitutes a target stimulus in a search experiment was emphasized by Kinchla (1974) who showed that after searching for an "O" among letters like:

```
xxxxx    x
  x      x
  x      x
  x      x
  x      x
  x      xxxxx ,
```

subjects are apt to respond that O is not present in a display like:

```
ooooo    o
  o      o
  o      o
  o      o
  o      o
  o      ooooo .
```

<u>Response Similarity of the Target and Noise</u>. As was noted at the beginning of the last section, stimulus similarity is an elusive concept. Perhaps this is because there is no general agreement about what is meant by a stimulus (Gibson, 1960). Gibson's conclusion was that no matter how one defines stimuli, they make good independent variables in behavioral experiments. Likewise, responses make good dependent variables, but so little is known about them that there is no basis for the kinds of disagreements about definitions that provoked Gibson's article on stimuli. This is because the physical phenomena which are the antecedents of stimuli are familiar, but the antecedents of responses are unknown. Nonetheless, we can operationalize response similarity as the extent to which two stimuli are

associated with the same response. If two stimuli evoke the same response, then they are response similar; if they evoke different responses, then they are response dissimilar.

Eriksen and Hoffman (1973) were the first to make the distinction between the effects of stimulus similarity and response similarity of visual noise and a target. Their experimental task was to press a microswitch to the left if H or M was presented or to the right if A or U was presented. The displays were twelve .2° letters around a circle, like numbers on a clock face. The letters were visible for 1 second after the subject initiated a trial, and were prececed (by as much as 350 msec) by a pointer which indicated the position of the target. The results showed that both response-similar noise (e.g., M for target H) or response-dissimilar noise (e.g., M for target A) slowed responses and increased errors compared with no noise. The two types of noise had parallel gradients of performance disruption versus distance of noise from target. However, performance was worse with response-dissimilar noise than with response-similar noise. The results were replicated by Eriksen and Eriksen (1974). These results imply that response-similar and response-dissimilar noise have the same effects except that the necessity of making a response decision in the presence of response-dissimilar noise requires extra time and involves extra opportunities for errors.

Slightly different results were obtained by Bjork and Murray (1977) who asked subjects to indicate which letter (B or R) was in a particular location of an array presented for 50 msec. There was a

separate response button for each potential target so a B in the context of other B's would exemplify response-similar noise and an R in the context of B's would exemplify response-dissimilar noise. Bjork and Murrav reported that response-similar noise especially impairs accuracy of identification of targets and that response-dissimilar noise tends to delay responses to the target. They elaborated a theory to explain these results which includes processing of visual information in a sequence of perceptual and decision-making levels. They asserted that response-similar visual noise interferes with information processing at the perceptual level by decreasing the accuracy of target identification. Response-dissimilar visual noise is purported to act at the decision-making level by delaying the response. This theory seems to be an oversimplification because Eriksen and Hoffman (1973) and Eriksen and Eriksen (1974) also found increased latency of responses associated with response-similar noise.

Prägnanz. Although the gestalt school of psychology is not very strong among modern American experimental psychologists, there is probably some truth to their tenet that a global stimulus is more than the sum of its component stimuli. This truth is reflected in the results of Banks and Prinzmetal (1976). They employed two experimental tasks in which subjects looked for letter targets: a search task in which search time was the dependent variable and a 50-msec tachistoscopic detection task in which the probability of detection and reaction time were the dependent variables. They found that performance was poorer if the target was part of a

gestalt of noise items (so that the target and noise had prägnanz) than if the target was not unified with the noise by a good gestalt.

To summarize, the useful field of view and time spent on fixations seem to be part of a system for adapting to visual complexity (Mackworth, 1976). According to Mackworth, the visual field narrows and fixations are protracted when the observer's perceptual capabilities become overloaded by visual noise. Background objects, or visual noise, interferes with search for targets. The magnitude of the interference increases with the similarity and proximity of the background to the target, the number of background items, the eccentricity of the target and background items in the field of view, and perhaps the pattern of items on the display. These findings indicate that any investigation of visual search should control the number of background items, proximity of noise to the target, and the similarity of the target and background. The effect of the pattern of objects on the display should be investigated as should the use of calculated color difference as a measure of color similarity.

Target Position

The position of the target on a display affects search time, even though all positions are equally likely in an experiment. For example, Baker, Morris, and Steedman (1960), Banks and Prinzmetal (1976), and Gordon and Winwood (1973) gave evidence that targets are found faster in the upper half of a display than in the lower half. This may be because people in western civilization have

a stereotypic top-to-bottom strategy for visual scanning due to reading habits.

Furthermore, the radial position of the target between the center and the outer edge of the display affects search time. Baker, Morris, and Steedman (1960) found that search times are protracted by as much as 30 percent when the target is near the edge of the display. Monk (1974, 1976, 1977) controlled the position of the target in his search experiments and found slower search times near the edge of the display.

An explanation of the edge effect found by Baker, Morris, and Steedman, and Monk is that eye movements avoid parts of the display near the edge. Enoch and Fry (1958) found that fixations tended to cluster near the center of a display and were rather sparse near the outer edge. Similarly, White and Ford (1960) showed that eye movements on a circular display tended to be concentrated halfway between the edge and the center of the display. This is where Baker, Morris, and Steedman found search times to be minimum.

Individual Differences

Significant differences among subjects' search performances have been noted by several authors (e.g., Green & Anderson, 1956; Baker, Morris, & Steedman, 1960; Smith, 1962; Erickson, 1964; Johnston, 1965, 1966, 1967; Carter, 1972; Snyder & Taylor, 1976). These effects can be isolated by using a repeated-measures experimental design. However, such a procedure does not clarify the

nature of the differences among subjects. For example, search speed may be affected by motivation and scanning habits reflected in reading speed (Boynton, 1960).

The most optimistic finding about a trait of individuals which might be related to search speed was that of Erickson (1964) who reported a correlation of .8 ($\underline{n}$ = 94, $\underline{p} < .001$) between his subjects' search times and their peripheral visual acuity. His method for measuring peripheral acuity was innovative, as was the idea that search depended upon peripheral acuity. To measure peripheral acuity, Erickson asked his subjects to indicate the orientation of a black Landolt-C presented for 1.5 seconds under natural viewing conditions. These targets were viewed binocularly at 8 feet with a background luminance of 176 foot-lamberts, and a contrast of .95. The targets were presented at eccentricities of 3.6, 4.8, or 6 degrees while the subject fixated a dark spot and steadied his head against a forehead rest. Erickson's subjects searched for C's among circles, or for blobs with small squares attached among squareless blobs. Search times were more highly correlated with acuity at 3.6° and 4.8° than at 6° eccentricity. Other interesting results were that peripheral acuity scores changed radically from week to week during the six weeks of the experiment and that peripheral acuity was unrelated to foveal acuity. Furthermore, other individual variables such as age, foveal acuity, and overall visual health on an aviator's eye examination were unrelated to search speed.

Erickson's finding of a relation between search performance and peripheral acuity seems sensible. Subjects presumably decide

where next to fixate on the basis of parafoveal information, so short search times should be related to ability to discern likely targets with parafoveal vision. However, the estimated strength of the relation between peripheral acuity and search speed is surprising. Johnston (1965) replicated and extended Erickson's experiment. She too used Landolt-C-type targets for a peripheral acuity test, and superimposed them on a perimeter at 13 inches from the subjects' eyes. Illumination at the perimeter was 2 ft-candles.

Johnston's subjects performed two types of search tasks: a search for a peripheral acuity test target with a different orientation than other targets in the field, and a search for the silhouette of a truck-mounted missle among other military silhouettes. The search materials were rear projected, and viewed at a distance of about 48 inches. Johnston found a statistically significant, but weaker relationship ($\underline{r}$ = .3, $\underline{p}$ < .05) than did Erickson between peripheral visual acuity acuity and search time.

Perhaps the explanation for the differences between Johnston's (1965) results and Erickson's (1964) results can be found in the research of Johnston (1967). She showed that acuity targets should be at the same distance from the observer as the search material will be. In other words, search performance for distant objects is more related to parafoveal acuity for distant objects than to parafoveal acuity for near objects. Erickson's research meets this condition whereas Johnston's does not, so it is not too surprising that Johnston's peripheral acuity-search time correlations were weaker.

However, when Erickson (1966) tried to repeat his earlier demonstration of the relationship of parafoveal acuity and search time, he found no significant relationship between acuity (peripheral or foveal) and search speed, even though the acuity test viewing distance and the search viewing distance were the same. Despite the disappointing "shrinkage" of the estimated strength of association between peripheral acuity and search speed, Snyder and Taylor (1976) recommend that "Peripheral acuity measures should be a good starting point for attacking the problem of striking individual differences in observer performance . . ." (p. 8).

Johnston (1966) showed that subjects who smoke tend to search less rapidly than nonsmokers, and that two weeks of abstinence from smoking improves the performance of smokers. The chain of causality inferred by Johnston was that smoking affects peripheral acuity and peripheral acuity affects search, so one would expect smoking to affect search performance.

Finally, variables such as foveal acuity, color vision, age, sex, recent drug consumption, and general visual health seem commonsense candidates for any study of individual differences in color-coded visual search. These variables would supplement reading speed, parafoveal acuity, and smoking habits data which are suggested by the literature to be related to visual search performance.

Overall, then, search performance is affected by many display and individual difference variables. These variables should be controlled (Fisher, 1971) in an experimental investigation of the effects of Target Class Size so that the estimate of experimental error will

not include variability attributable to display density, background objects, target position, and individual differences.

Why Color Coding?

One could imagine many tasks that would require subjects to use information from abstract displays, and many ways to code the information on the displays. Examples of tasks include identification, counting, verifying, locating, or comparing information on the display. The codes could use numbers, geometric shapes, letters, colors, configurations of simpler elements, or silhouettes of equipment. It has been found that the relative effectiveness of types of codes depends upon the task (Hitt, 1961; Smith, 1963). Color is generally superior to other coding methods when the task is to find information on the display (Christ, 1975; Christ & Corso, 1975; Cook, 1974; Demars, 1975; Eriksen, 1952; Hitt, 1961; Jones, 1962; Williams, 1966a, 1967a, 1967b, 1973). Color has the added advantage that it can be combined with other codes without adding more symbols to the display. Colored digits, for example, require the same number of symbols as uncolored digits. In general, color coding is used for a search task because it results in better performance than any other code.[1]

Color coding is also studied because it is not known why color coding is better than other coding methods. However, its superiority for a search task is consistent with the results of other color research. For example, Von Wright (1970) demonstrated that if a person is shown an array of symbols and is asked to recall symbols with a

given cue characteristic immediately after termination of the array of symbols, then performance is best if the recall cue is color. Hence, color may aid search because color can be retrieved most rapidly from visual immediate memory. In addition, Cavanagh (1972) summarized evidence that memory span and mental scanning rate for color are superior to those for all other symbols (e.g., shapes, random forms, letters, syllables, and others) except numbers. The rapid scanning rate leads to rapid recognition of colored targets, which has obvious implications for visual search. Finally, color may be a better search code than letters, numbers, shapes, etc. because these alternative codes rely on peripheral acuity, which is notably poor. Color does not degrade as rapidly as acuity in peripheral vision. One can demonstrate this for oneself by moving a colored letter away from the line of sight. The color will be apparent long after the letter is unrecognizable.

These two reasons for research on color coding, improved search performance and unknown mechanism of action, are perhaps secondary to the importance of making each new study comparable with past research. Barker and Krebs (1977) documented a tradition of at least 16 investigations of color coding of visual search tasks. Those who seek to extend and modify the accumulated knowledge about search should include color coding as an aspect of their work so that it will be clearly related to work already done.

General Objectives of This Research

The primary objective of this research was to show the effect of the number of items of the same color as the target, or the Target Class Size (TCS), when the subject knows the color of the target. TCS can vary in magnitude from one item to a maximum value equal to the display density. Several other variables also known to affect search time, such as target position, individual differences, the number of items adjoining the target, and display density, were controlled. The effects of these experimentally controlled variables were verified, and their interactions were examined. In addition, control of these variables provided more precise estimates of the effects of TCS and other variables of interest.

The nature of individual differences in search speed was investigated. Search speed was estimated for each subject, and as expected, based on results summarized in the literature review, some subjects were faster searchers than others. An attempt was made to identify those personal characteristics of the subjects which typify rapid or slow searchers. Several possible characteristics were chosen on the basis of the literature review: foveal and parafoveal visual acuity, reading speed, smoking habits, recent drug use, general visual health, and color vision.

Another objective of this research was to investigate the relation between physically derived measures of color difference and search-related psychological variables. Two such psychological variables are the frequency of looking at the wrong color when the

target's color is known (Williams, 1967a) and search time. These two psychological variables were studied as they are affected by the color difference between the target and background items. Color difference was measured by a new color-difference formula (Robertson, 1977). This formula is a function of the spectral distributions of light in the colors whose difference is to be calculated.

Additional research opportunities suggested by the results of these investigations were also pursued. Such opportunities included effects of the number of non-target-colored (background) objects, random versus patterned placement of target-class objects, the color of objects adjoining the target, and practice during the subject's session.

Finally, the data obtained in this research were studied as cumulative probability distribution functions (CDF). The CDF describes the probability that the target will be found within any given amount of time. Other researchers have found that search data are well described by an exponential CDF, although alternatives have been suggested. These CDF models of search time were compared for congruence with the data.

CHAPTER 2

METHOD

The method of investigation was the same throughout the experiments reported and was quite similar to that used by Carter (1972). The method had a number of components: the dependent and independent variables, the experimental design for combining the independent variables, the apparatus which controlled the independent variables and measured the dependent variables, the procedure for using the apparatus, and the subjects. Each of these components is described in detail in the sections to follow.

Variables

Search time was chosen as the dependent variable to represent search performance. The choice was made primarily to maintain continuity with other work which is related to this research (Cahill & Carter, 1976; Carter, 1972; Carter & Cahill, 1979; Green & Anderson, 1956; Green, McGill, & Jenkins, 1953; Smith, 1962, 1963).

Search time is a good dependent variable because it is correlated with other aspects of search performance such as the duration of fixations, the frequency of fixations on nontarget objects in the search field, and interfixation distance (Williams, 1967a; Gould & Dill, 1969; Snyder & Taylor, 1976). Search time represents search errors, too, because errors like glances at the wrong object or

looking at the target without seeing it (Mackworth & Mackworth, 1958) compound search time. Finally, search time has a high utility because it includes much of the information offered by other dependent variables, like eye movements, yet the cost of measuring it (in effort and money) is several orders of magnitude less than the cost of those other variables.

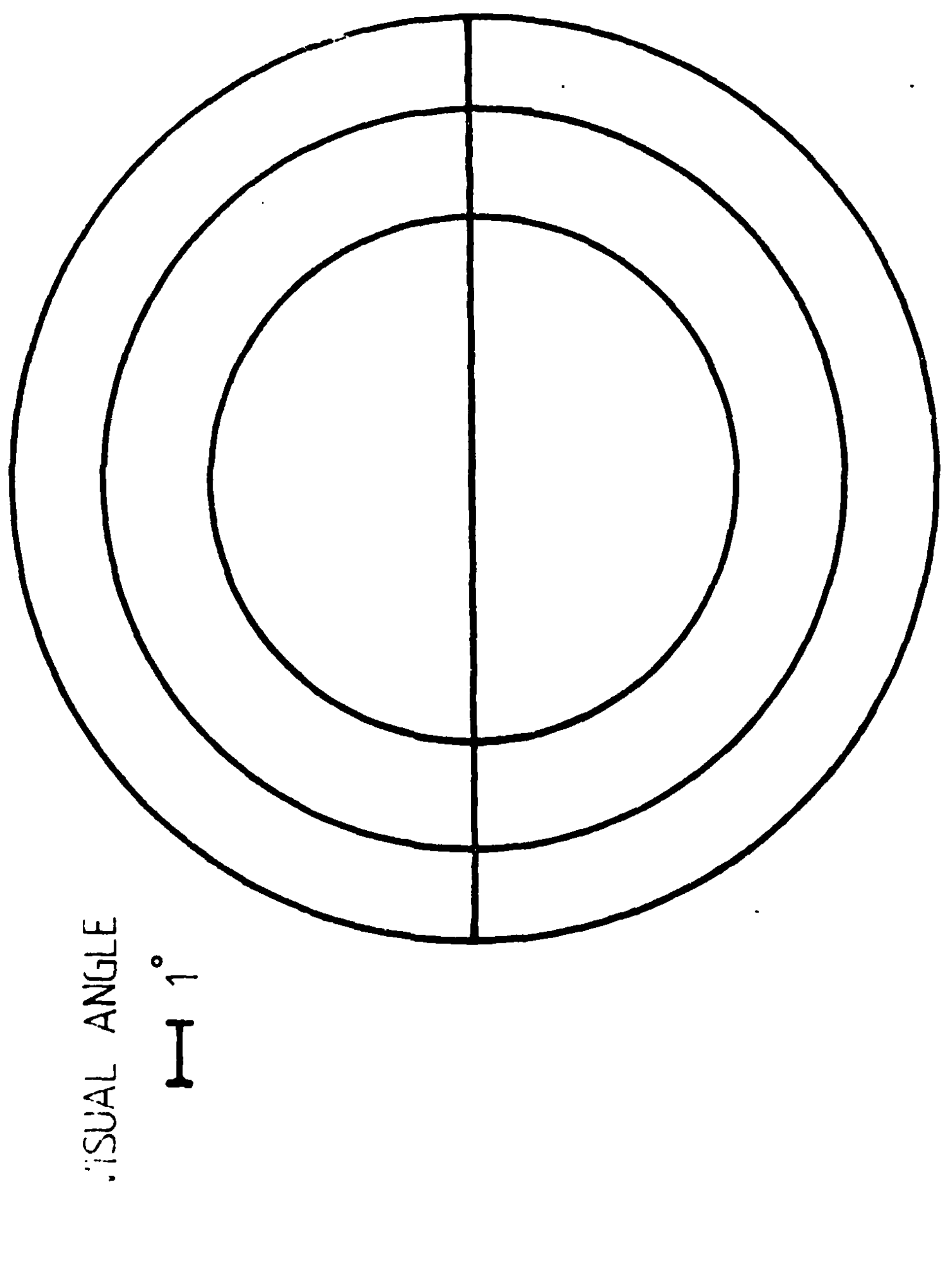
The primary independent variables in this investigation were the number of displayed items of the same color as the target (TCS), the number of items not of the target color (background items), and the similarity of the target and background colors. Other independent variables which were experimentally controlled were discussed in the literature review: display density, target placement in the top or bottom half of the display, proximity of the target to the outer edge of the display, and the number of items adjoining the target. Intersubject variability was also controlled by using a repeated-measures design. A final independent variable which was experimentally controlled is replication. This variable was suggested by an anonymous reviewer of Carter and Cahill (1979). He offered the possibility that search times observed for a particular display might reflect an "unfortunate randomization" instead of the conditions the display was intended to represent. In the present experiment, two different displays (generated independently and having randomization of uncontrolled variables) were used to represent each experimental condition. The extent to which these pairs of displays produced identical search times was a measure of the replicability of the experiment, or freedom from "unfortunate randomization."

Experimental Design

The experimental design was factorial with repeated measures. All of the variables discussed in this section were generally within-subjects variables. Some between-subjects variables (e.g., TCS) will be named in later descriptions of particular experiments.

Display density was 60 items or 30 items. These values were chosen because they are large enough to allow color coding effectively to reduce search times (Cahill & Carter, 1976). The targets were placed in the top or bottom half of the circular displays, and their distance from the edge of the display had three levels. A central disc and two concentric annuli, all of equal area, defined the levels of distance from the edge (see Figure 1). The outer annulus extended about 1.5° visual angle from the edge of the display to its center, and the diameter of the inner disc was about 9°. The number of items adjoining the target was 0, 1, or 2. There were 36 experimental conditions defined by the factorial combination of density (2 levels), half (2), edge distance (3), and neighbors (3). The order of these conditions was randomized for each subject. Of course, replication doubled the number of conditions. Each of the two replications was equally often viewed first in any experiment, so replication was not confounded with practice. All subjects searched displays representing all 72 within-subjects conditions.

Figure 1. Schematic of Display Regions for Target Placement.


ISUAL ANGLE
1°

Apparatus

The apparatus had several components: displays, console, light box, and timer. The purpose and structure of these components will now be described. (Auxiliary apparatus for particular experiments will be described with the pertinent experiment.)

Displays

The displays were 11.5-inch (29.2 cm)-diameter circular photographic negatives with clear .38-inch (.95 cm)-high three-digit numbers presented on an opaque background. The numbers were oriented horizontally. The first two digits of each three-digit number (display item) were unique on that item's display, and all three numbers of each item were chosen at random, subject to the constraint of uniqueness. Each display had one target item.

The 72 displays required by the experimental design were constructed in the following way. Targets were located at random within the upper or lower half of a display, and at a particular distance from the edge of the display, as required by the experimental design. Once the location of the target was specified, 0, 1, or 2 other items were placed adjoining the target, also in accordance with the experimental design. These neighboring items were placed randomly at the left, right, above, or below the target. Diagonally adjacent items were forbidden because Brown and Monk (1975) show that diagonal neighbors have little effect on search time. After the target and its surround had been established, additional items were

placed at random in the 230 locations on the display, excluding positions in the target's surround, until the required density had been achieved. Displays representing two independent replications of the complete set of 36 experimental conditions were produced in this manner.

The display items were colored using Roscolene[2] colored transparencies. A set of five colors was chosen to be used in this experiment (see Appendix A for color specifications), and display items were coded with colors chosen at random from this set. The color of the target class items on each display was also chosen at random. The color coding of each of the 72 displays was changed for each of the experiments to be described.

Console and Light Box

The displays were viewed from a distance of 45 inches (1.14 m) in a console similar to that of an air-traffic controller. The face of the console was about 1 m square with a reflected luminance of about .24 mL.[3] In the center of the console face, at eye level, was an 11.5-inch (29 cm)-diameter circular display screen, which was recessed about 1 inch (2.54 cm) behind the display face. The screen was made of partially crossed polaroids (8.3% transmission) so that an observer could not see through the screen unless there was a bright light behind it. The reflected luminance of the screen was 0.00366 mL. The console face and screen were mounted at an angle of 15 degrees from vertical so that specular reflection to the observers' eyes came from black sponge material draped from the ceiling behind the observer.

A light box was placed behind the display screen. The aluminum-foil-lined box contained four 25-watt incandescent light bulbs which were placed so that a sheet of opal glass at one end of the box was uniformly illuminated. The luminance of the box when viewed through the display screen was 4.3 mL.

The search displays of three-digit numbers were sandwiched between the light box and the display screen so that a display could be made to appear or disappear depending upon illumination of the light box. Illumination of the light box was controlled by a push button held by the subject.

Timer

A Standard Electric Time Corporation timer (Model S-1) was used to measure search time. The timer and the light box were on the same electrical circuit so that they operated simultaneously when the subject pressed his control button. The illumination of the light box changed by 90 percent within 0.05 second of operation of the push button. For all practical purposes, then, the timer measured the amount of time that the search display was made visible by the light box. Because the observer could search the display only when the numbers were visible, search time was equated with the amount of time that the search display was made visible. The timer was reset before the observer searched each display, and the time required to find the target on a display was the basic datum of this research.

Procedure

A subject was seated so that his eyes were about 45 inches (1.14 m) from the display screen. At this viewing distance a digit on the display subtended about 30 minutes of visual angle, which is well above the minimum of 20 minutes of angle recommended by Jones (1962) to eliminate the problem of small-field achromaticity. The subject sat in an ordinary straight chair without arms and was not restrained by a headrest or bite-board. Use of such devices was undesirable because in most applications the user enjoys freedom of head and upper-body movement. However, a cord was placed at the subject's forehead and parallel to the face of the console to prevent gross deviations from the viewing distance of 45 inches (1.14 m).

When the subject was ready, he pressed the button to reveal a column of 1-inch (2.54 cm) by 0.5-inch (1.27 cm) rectangles of the five colors used to code the displays. The subject reported the names he preferred for these colors. The names chosen by the subject were used by the experimenter to tell the subject the color of the target before each display.

The standard instructions (Appendix B) were then given to the subject. Following the instructions the subject began to look for targets on the displays. In advance of presentation of each display the subject was told the first two digits and the color of the target. When he was ready, the subject pressed the button (and thus presented a display), found the target, noted its third digit, and released the button (thus terminating the display). The search was to be made as

rapidly as possible, consistent with an errorless report of the third digit. (No error was made by any subject.) The amount of time the subject held down the button was recorded as the search time.

This procedure was repeated for as many as 72 displays for each subject. A session lasted about one hour. At the end of a session the subject was informed of the general results of this research.

Subjects

Subjects were unpaid volunteers solicited from introductory psychology classes at The Pennsylvania State University who received credit toward their grade for participation. Men and women were equally represented, and their ages ranged from 17 to 35 years. A more complete description of the subjects is given in the chapter on individual differences, which deals with a subsample of 78 (37%) of the 212 subjects who participated.

CHAPTER 3

EXPERIMENT I: TARGET CLASS SIZE

The single question about color coding and visual search which has been most in need of additional investigation is the effect of the number of display items which share the target's color (Smith, 1971). This variable has been named Target Class Size (TCS), and has been shown to have a predominant effect on search time (Green & Anderson, 1956; Carter & Cahill, 1979). However, TCS has been experimentally controlled only on a display of density 60, and only in the range of 10 to 60 items. In this range, average search time increases approximately linearly with TCS. Two specific issues needing clarification are whether this TCS effect can be generalized to display densities other than 60, and the effect of reducing TCS to 1, its minimum value. The search time obtained with TCS = 1 would indicate whether the search time versus TCS curve continues the trend set when TCS is greater than 10, or, alternatively, levels off for small values of TCS, as suggested by Gordon and Winwood (1973) and Schontz, Trumm, and Williams (1971).

Experimental Design

The experimental design was a split-plot factorial (Kirk, 1968). Four independent groups of 18 subjects responded to four variations of the basic 72-display sequence representing a factorial arrangement

of density, target position, and the number of display items adjoining the target. In one variation (Experiment Id) the numbers on the displays were white; there was no color coding and TCS was equal to the display density. In Experiments Ia, Ib, and Ic, the displays were color coded with Target Class Sizes of 1, 10, and 30, respectively. Hence, the degree of color coding was a between-subjects variable, and density, target position, and the number of items adjoining the target were within-subjects variables.

Results and Discussion

The mean search time for each combination of TCS and display density is listed in Table 1. Analyses of Variance (Table 2) indicate that the effects of TCS, display density, and their interaction were statistically significant in both raw scores and log-transformed data, and that the effects were replicable. TCS and display density are identical on the black-and-white displays, and they had a significant effect on search time. This effect did not change on replication of the experiment. Identical conclusions were drawn from analyses of log-transformed scores for black-and-white displays. The interaction of TCS and density, including colored and black-and-white displays, is shown in Figure 2.

The most striking aspect of this figure is that when TCS was varied through its full range (from 1 to the display density), mean search time changed by more than 500% or 1000% when display density is 30 or 60, respectively. This remarkable change of search time demonstrates the power of color coding for shortening search times.

Table 1

Effects of Target Class Size and Display Density

TCS	Display Density 30	60
1	0.97[a]	1.02
10	2.33	2.81
30	4.82	5.66
Black and White	5.60	11.62

[a]Mean Search Time in seconds, N = 648.

Table 2

Analysis of Variance for Search Time[a] in Experiment I

Source	df	MS	F	MS_{log}	F_{log}
Color-Coded Displays					
Between Subjects					
Target Class Size (TCS)	2	5,969.29	132.71**	142.34	292.82**
RS (TCS)	51	44.98		.49	
Within Subjects					
Display Density (D)	1	201.50	19.47**	2.10	41.76**
TCS X D	2	51.34	4.96*	.21	4.17*
RS X D (TCS)	51	10.35		.05	
Replication (R)	1	11.99	1.71	.02	.26
TCS X R[b]	2	12.84	1.83	.08	.89
RS X R (TCS)	51	7.02		.10	
D X R	1	6.99	.97	.00	.00
TCS X D X R	2	4.27	.59	.08	2.34
RS X D X R (TCS)	51	7.22		.03	
Black-and-White Displays					
Between Subjects					
TCS	1	9,269.72	52.17**	20.72	169.24**
RS (TCS)	17	177.70		.12	

Table 2 (Continued)

Source	df	MS	F	MS_{log}	F_{log}
Within Subjects					
R	1	291.99	2.09	.01	.08
TCS X R	1	22.11	.18	.002	.02
RS X R (TCS)	17	139.66		.11	

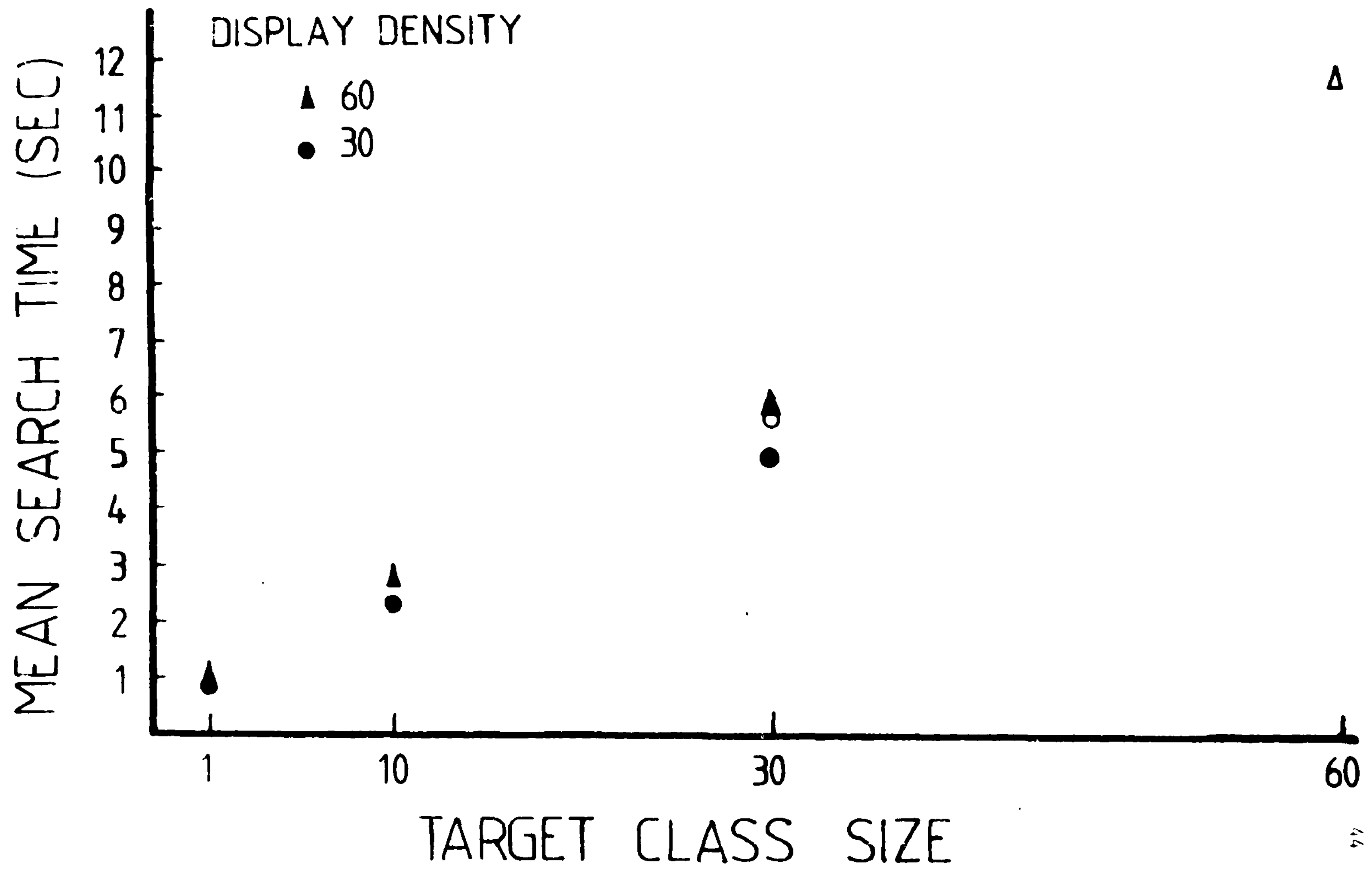
[a]Analyses of search time and log search time are presented.

[b]A significant interaction of replication and another source indicates that the effect of that source changed upon repetition of the experiment.

* $p < .05$

** $p < .01$

Figure 2. Mean Search Time Versus Target Class Size.


DISPLAY DENSITY
60
30
MEAN SEARCH TIME (SEC)
12
11
10
9
8
7
6
5
4
3
2
1
1
10
30
60
TARGET CLASS SIZE

Even more spectacular savings of search time would be expected with greater display densities.

The interaction of TCS and display density represents the convergence of the curves for density 60 and density 30 as TCS diminishes. Apparently, the effect of display density is negligible when TCS is 1, but search time becomes dependent on density as TCS becomes larger. Carter and Cahill (1979) also found that search time depends on density in addition to TCS. Although no rigorous theory is proposed for this effect of density, it seems that the effect of density must be due to items not of the target's color. This is because display density equals TCS plus the number of items not of the target's color (background items), so the only aspect of density which is independent of TCS is the number of background items. Perhaps subjects do not notice the background items when there is but one item of the target color (TCS = 1). However, when TCS is 30, the search is prolonged so there are more opportunities for background items to interfere with the search.

A puzzling aspect of Figure 2 is that search time for black-and-white displays was longer than for colored displays when density and TCS were 30 (Behrens-Fisher $\underline{t}^* = 2.55$, $\underline{p} < 0.05$). Smith (1962) reported that the color of the targets on a display made almost no difference in his experiments. It is suspected that the present results for the black-and-white case were due not to color or its absence, but rather to the range of stimuli to which the subjects were exposed. The results for colored targets were obtained from subjects who produced relatively homogeneous search times for density

30 or 60 at TCS 30. In contrast, the black-and-white results were obtained from subjects who searched displays on which the average search time for density 60 was double that obtained for density 30. The search times for density 30 with black-and-white displays may have increased slightly due to the long searches that subjects sometimes enacted when display density was 60.

The results portrayed in Figure 2 indicate that the mean search time versus TCS curve in the interval from TCS 10 to TCS 1 continues the trend set when TCS is greater than 10. Figure 2 does not support the contention of Schontz, Trumm, and Williams (1971) and Gordon and Winwood (1973) that the search time versus TCS curve levels off when TCS is small.

Table 3 shows the analysis of linear models having different trends for density 30 and density 60, as necessitated by the TCS by density interaction in Table 2. Models which have identical or different values for the TCS 1 intercept are compared, and the data are fit best by a model in which the density 60 and density 30 trends meet when TCS is 1. In other words, density seems to have no effect when TCS is 1. The best linear model explains 99.7% of the variance of mean search times.

To summarize, search time can be reduced by an order of magnitude (when display density is 60) if the target is coded in a unique color. Even more improvement of search performance with color coding is expected for display densities in excess of 60. As the number of items of the target's color (TCS) increases, the mean search time increases approximately linearly. The maximum value of TCS is the

Table 3

Linear Models of the TCS-by-Density Interaction

Model 1: $Y = b_{30} + b_{60} + b_1 (TCS_{30} - 1) + b_2 (TCS_{60} - 1)$

Source	df	SS	MS
Regression	4	236.351	59.09
Residual	4		0.152

Model 2: $Y = b_0 + b_1 (TCS_{30} - 1) + b_2 (TCS_{60} - 1)$

Source	df	SS	MS
Regression	3	236.351	78.78
Residual	5		0.121

Model 1 versus Model 2

Source	df	SS	F	
Extra Sum of Squares for Model 1	1	0.0005	0.003	Therefore, retain the simpler Model 2
Residual	4	0.152		

display density. Display density is the number of items on the display, and it includes TCS and the number of background items. The effect of background items appears to interact with TCS. The possibility of a TCS-by-density interaction will be explored in the next experiment.

CHAPTER 4

EXPERIMENT II: BACKGROUND ITEMS

Experiment I established that the number of items which share the target's color (TCS) has an overwhelming effect on search time, but one could also ask about the effect of items not of the target's color. If we note that display density equals TCS plus the number of items of a different color than the target (background items), then it is apparent that the effect of density in Experiment I was due to the part of density which is independent of TCS: background items. Increasing the number of background items seems to have almost no effect on search time when TCS is 1 in Experiment I, yet the effect became quite pronounced as TCS increased to 30. This is an interaction of TCS and the number of background objects, and it suggests that TCS and the number of background objects be investigated in a factorial experiment.

Experiment II was such an experiment. It also provided an opportunity for examination of other phenomena related to TCS and background items. For example, similarity between the background items and the target has an important effect on search performance, as discussed in Chapter 1. Hence, the similarity of target and background was controlled in Experiment II. Another interesting phenomenon, possibly related to TCS, is a "range effect" (Poulton, 1973). In Experiment II, TCS was a within-subjects effect, so that

the extent of TCS range effect was indicated by comparison with the effects of the same values of TCS in a between-subjects experiment (Experiment I).

Experimental Design

Experiment II was intended to answer several distinct questions: (1) Do TCS and the number of background items interact? (2) What is the effect of similar or dissimilar background items? (3) How does search time depend on the number of background items? and (4) Are there appreciable range effects when TCS is a within-subjects variable?

The experiment was conducted in five parts which represented combinations of the number of background items and their similarity to the target. Five independent groups of 18 subjects participated in Experiments IIa, IIb, IIc, IId, and IIe. In Experiment IIa there were no background items. In Experiments IIb and IIc there were 29 background items, which were dissimilar or similar (respectively) to the target. Experiments IId and IIe had 59 background items. The target was always light purplish red (see Appendix B), and the background items were dark purplish red or green when the target-background similarity was high or low, respectively.

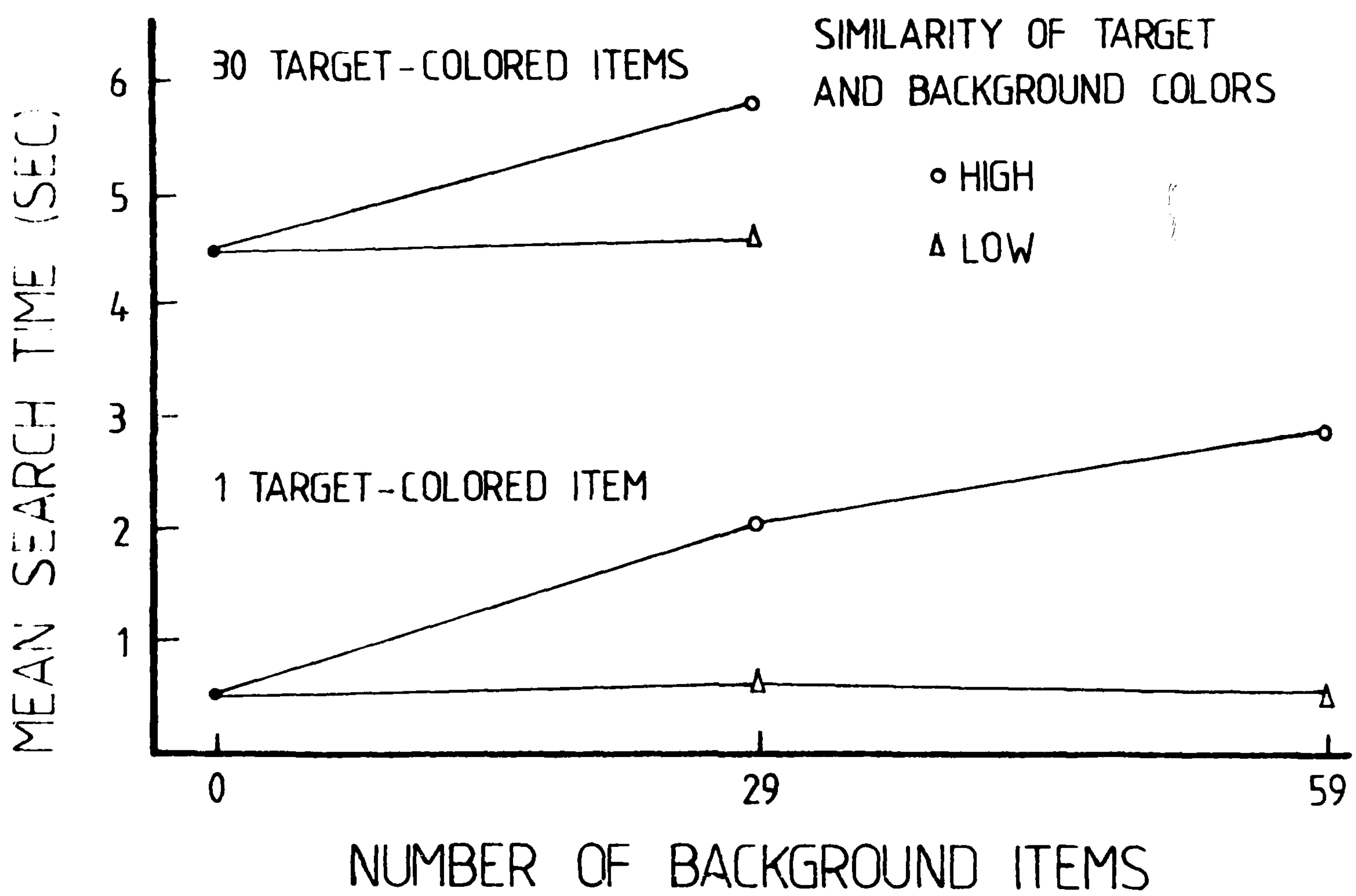
Each subject searched displays representing the target position and target neighborhood variables discussed in Chapter 2. TCS was an additional within-subjects variable in this experiment, and had values of 1 or 30. Experiments IId and IIe are exceptional in this regard because they included only a TCS of 1. This is because the

search displays had a maximum of 60 items, so it was impossible to achieve a TCS greater than 1 when the number of background items was 59, as it was in Experiments IId and IIe. Subjects in these two experiments searched 36 displays, and the subjects in Experiments IIa, IIb, and IIc searched 72 displays.

Results and Discussion

The results of Experiment II are depicted in Figure 3, and the mean search time (N = 648) for each experimental condition is listed in Table 4. The experiment was analyzed in two parts (see Table 5). Experiments IIa, IIb, and IIc were analyzed first. There was no indication of interaction between TCS and the number of background objects. (The significant interaction in the analysis of log-transformed data is due to alteration of the scale of search times by the transformation.) TCS and the number of background items had strong effects. None of these effects interacted significantly with replication in either raw-score or log-transformed analyses. Dunnett's test (Kirk, 1968; critical value of $d'(0.01, 3, 51)$ = 0.49 sec) indicates that 29 similar background items increased search time appreciably compared with no background items, but that search time was virtually unchanged by background items which were very different from the target.

Results for TCS = 1 were reanalyzed to include Experiments IId and IIe with 59 background items. The number and similarity of background items again had a strong effect which did not interact with replication in raw-score or log-transformed analyses. Dunnett's



30 TARGET-COLORED ITEMS
1 TARGET-COLORED ITEM
SIMILARITY OF TARGET
AND BACKGROUND COLORS
HIGH
LOW
MEAN SEARCH TIME (SEC)
NUMBER OF BACKGROUND ITEMS
0
29
59
1
2
3
4
5
6

Table 4

Effect of Background Items on Mean Search Time (Seconds)

Number of Background Items	TCS = 1		TCS = 30	
	Similar Background	Dissimilar Background	Similar Background	Dissimilar Background
0	0.53[a]		4.45	
29	2.03	0.62	5.77	4.55
59	2.82	0.52		

[a]When there are no background items they can be neither similar nor dissimilar to the target.

Table 5

Analysis of Variance for Search Time[a] in Experiment II

Source	df	MS	F	MS_{log}	F_{log}
Experiments IIa, IIb, and IIc					
Between Subjects					
Number and Similarity of Background Items (B)	2	804.07	37.15**	39.42	175.16**
RS (B)	51	21.64		.23	
Within Subjects					
TCS	1	14,530.58	693.00**	408.17	3,243.00**
B X TCS	2	3.86	.18	17.78	141.25**
TCS X RS (B)	51	20.97		.13	
Replication (R)	1	6.36	.46	.01	.08
B X R[b]	2	1.51	.11	.01	.09
R X RS (B)	51	13.84		.08	
TCS X R	1	10.40	.76	.02	.33
B X TCS X R	2	1.50	.11	.00	.04
T X R X RS (B)	51	13.73		.07	
TCS = 1, Including Experiments IId and IIe					
Between Subjects					
B	4	732.08	80.92**	314.89	263.00**
RS (B)		9.05		1.20	

Table 5 (Continued)

Source	df	MS	F	MS_{log}	F_{log}
Within Subjects					
R	1	.00	.00	.25	.84
B X R	4	.18	.05	.20	.64
R X RS (B)	85	3.66		.31	

[a]Analyses of search time and log search time are presented.

[b]A significant interaction of replication and another source indicates that the effect of that source changed upon repetition of the experiment.

** $p < .01$

Figure 3. Mean Search Time Versus Number of Background Items.

test (Kirk, 1968; critical value of d' (0.01, 5, 85) = 0.48 sec) indicated, once again, that background items which were very different from the target did not increase search time, compared with the effect of no background items. It is remarkable that dissimilar background items had no effect, even when they constituted more than 98% of the items on the display. However, when the background items were similar to the target, and TCS was 1, 29 background items produced longer search times than no background items, and 59 background items produced yet longer search times. [The critical value of Tukey's HSD ($p < 0.01$) for comparing mean search times for 29 similar items with 59 similar items is .44 sec; Kirk (1968).] There was a diminishing effect of additional background items, at least when TCS was 1, as indicated by the significant quadratic trend in search time as the number of background items increased from 0 to 29 to 59 ($F(1,85) = 6.79$, $p < 0.05$).

TCS was a within-subjects variable in Experiment II, so there may have been a TCS range effect in this experiment. Table 6 lists search times ($N = 648$) from comparable conditions in Experiment II and Experiment I (in which TCS is a between-subjects variable). These data were analyzed for range effects, using a method described by Games (1977) and elaborated by Erlebacher (1977). Apparently, there were TCS range effects in Experiment II because the within-groups search times were shortened for TCS 30 and prolonged for TCS 1, compared with search times for the same values of TCS and 29 background items in Experiment I ($Z = 10.1$, $p < 0.01$). There was no simple effect of within-groups versus between-groups treatments ($Z = .80$, $p > 0.05$).

Table 6

Target Class Size Range Effects

		Mean Search Time (Seconds)	
TCS	NOB[a]	Experiment I TCS Between Subjects	Experiment II TCS Within Subjects
1	29	0.97	1.33
30	0	5.60	4.45
30	29	5.66	5.16

[a]Number of background items.

These range effects should not automatically be classified as "unwanted," as Poulton (1973) does. Whether or not they are wanted in an experiment depends upon the situation to which one intends to generalize the results of the experiment. For instance, if one intended to generalize to a situation in which TCS is always 1 or 30, then Experiments Ia or Ic, respectively, would be most accurate because they lack effects due to the range of TCS viewed by the subject. In contrast, if one wanted to generalize to a situation in which a display operator searches displays on which TCS is sometimes 1 and other times is 30, then Experiment II would be more relevant because it includes range effects which are present in the operator's situation.

In summary, the number of background items and their similarity to the target have the same effect irrespective of Target Class Size. Background items which are of a color which is sufficiently dissimilar to the target color have no effect on search times. However, if the background items are of a color similar to that of the target, search times increase substantially as the number of background items increases. Finally, there can be changes of search times due to the range of Target Class Size experienced by a person. These changes may alter the search times expected in response to a particular value of TCS.

CHAPTER 5

COLOR DIFFERENCE

The results of Experiment II emphasize the importance of the similarity of the target and background objects. Similar background objects prolong search and very dissimilar background objects do not slow search compared with times obtained with no background objects. In the literature review it was noted that colors can be represented as points which are separated by a distance (or difference) in color space. Williams (1967a) has successfully used the distance between the points as a predictor of the similarity of colors. Williams measured distances along only a single dimension of Munsell (1963) color space (hue, value, or chroma). However, more general measures of color difference are available (Judd & Wyszecki, 1975) and may allow predictions of the similarity of colors which differ simultaneously in multiple dimensions of color space. The objectives of this chapter are to examine color difference as a predictor of color similarity data published by Williams (1967a) and to show how search time relates to the color difference between the target and background objects.

Williams' Relative Fixation Rate Data

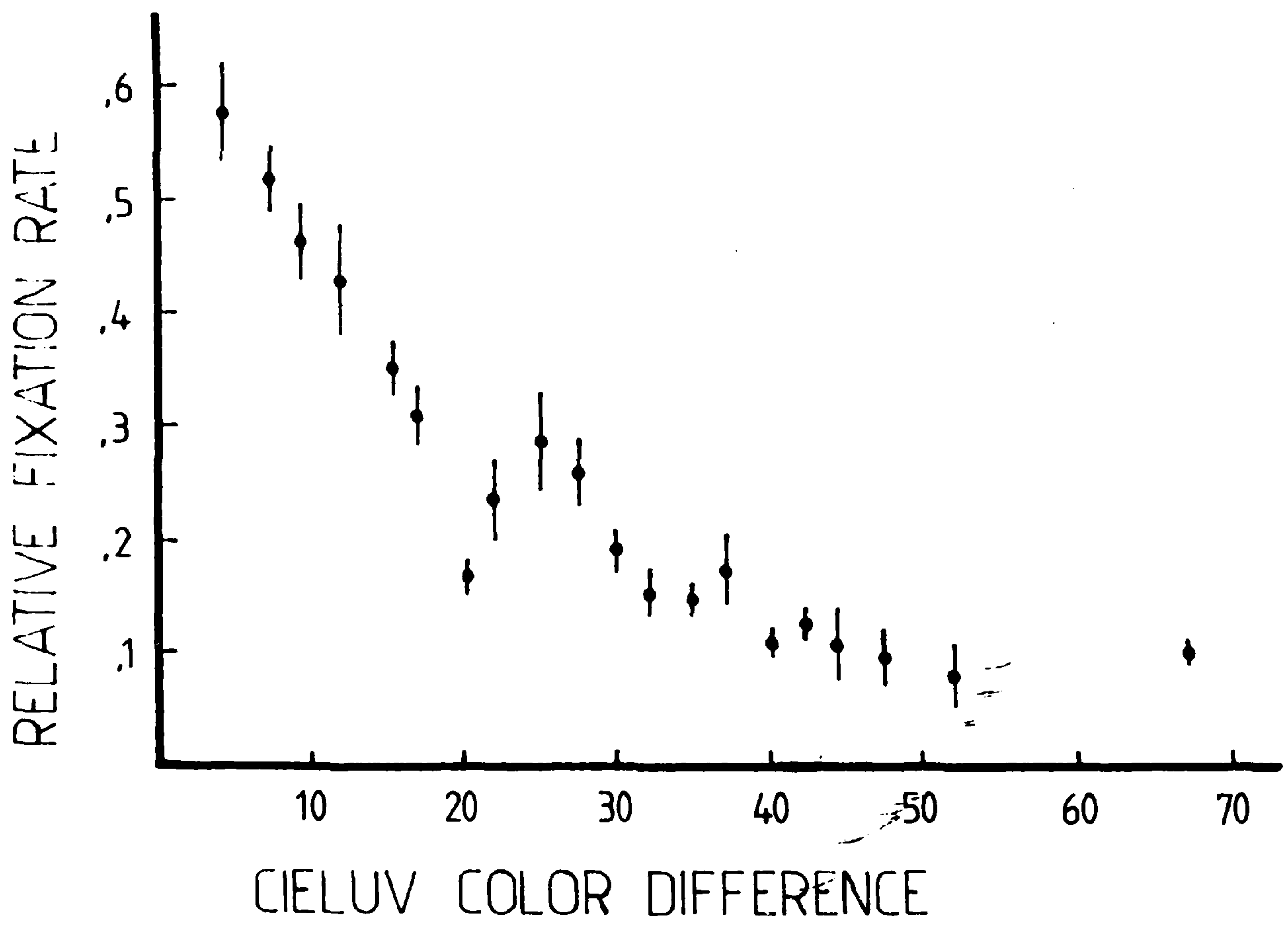
Williams (1967a) has published a table of Relative Fixation Rates (RFR or S_i) on background items as a function of differences in

(Munsell, 1963) hue, value, and chroma between the target and the background object. The RFR are normalized (divided) by the frequency of fixations on target-colored objects on the same display, so that the rates will be comparable across pairs of colors. RFR is a measure of similarity of colors because a small value indicates that a (dissimilar) background color was rarely mistaken for the target color, while large RFR value indicates that a background color was often looked at instead of the target color.

Williams' search displays had a density of 78, TCS was always 6, and 17 colors were used to code each display. The target on each display was a trapezoid of color, and the other display items were parallelograms of color selected to vary systematically from the target color in hue, value, and chroma. Subjects searched for the targets on the displays, and their eye movements were recorded. These eye-movement records were used to generate the RFR data for 383 pairs of target and background colors.

In order to test the notion that RFR is related to color difference, Williams' colors were translated from Munsell notation to CIE color notation using the table provided for that purpose by Wyszecki and Stiles (1967). Color differences were calculated using two color-difference formulae: CIELAB and CIELUV (Robertson, 1977). When plotted (Figure 4), the relationship of Relative Fixation Rate to color difference is a typical peaked discrimination gradient. The strength of the relationship may be assessed by coefficient eta (Winer, 1971). Eta is 0.80 for CIELAB versus RFR, and 0.78 for CIELUV

Figure 4. Relative Fixation Rate Versus CIELUV Color Difference.



,6
,5
,4
,3
,2
,1
RELATIVE FIXATION RATE
10
20
30
40
50
60
70
CIELUV COLOR DIFFERENCE

versus RFR. Hence, about 64 percent of the variance of RFR is accounted for by color difference.

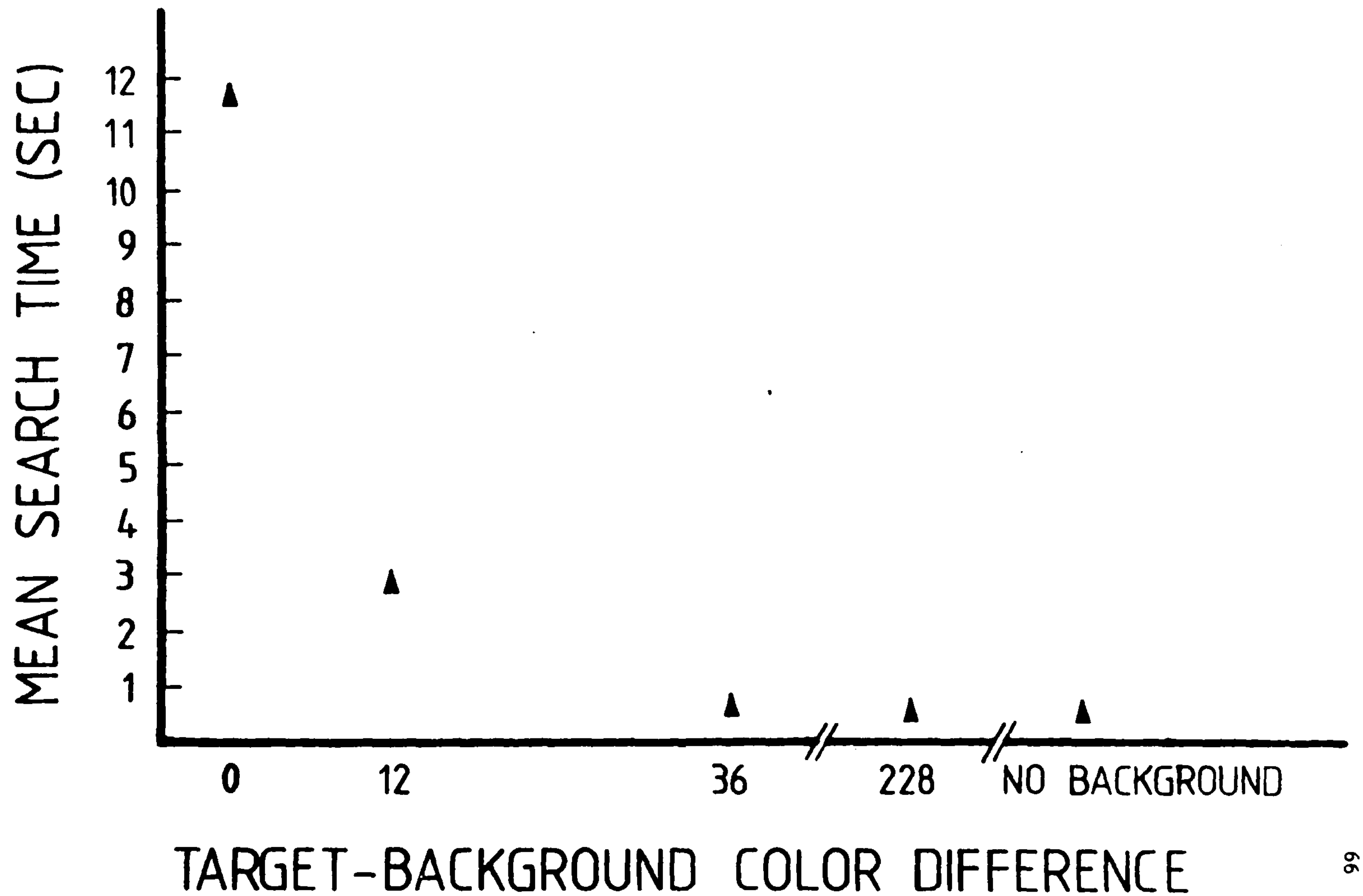
The moderately strong dependency of Relative Fixation Rate on color difference enables us to predict the proportion of fixations on background items when given the color difference between the target and background. This proportion of fixations is the basis of Williams' equation (1967a) for predicting search time. As an example of the effect on search time of the color difference between target and background, the "similar background" condition in Experiment II represents a target-background difference of 12 CIELUV units. The "dissimilar background" condition represents a CIELUV difference of 228 units. The color difference determined whether the background objects doubled the search time or had no effect in Experiment II.

Experiment III

The effect of color difference between target and background objects on search time can be analyzed in more detail by using data from previous experiments in which color difference was controlled, and data from 18 subjects in Experiment III. Searches were conducted with single targets among backgrounds which varied in color difference from the target. In Experiment III display density was 60, TCS was 1, the target-background color difference was 36 CIELUV units, and the within-subjects variables were as described in Chapter 2.

The resulting search times are plotted versus target-background color difference in Figure 5. Search times are protracted by a small color difference between target and background, and the times are as

Figure 5. Mean Search Time Versus Target-Background Color Difference.


MEAN SEARCH TIME (SEC)
12
11
10
9
8
7
6
5
4
3
2
1
0
12
36
228
NO BACKGROUND
TARGET-BACKGROUND COLOR DIFFERENCE

low with a 36-CIELUV-unit target-background difference as with no background. The close correspondence between these results and those for RFR should be noted; the RFR versus color-difference curve also reaches an asymptotic value at about 40 CIELUV units. This finding supports Williams' (1967a) contention that search time is directly related to RFR.

Several applications of the relation of color difference to search performance are apparent. For example, color difference could be used as a criterion for choosing any number of colors for a color code. Colors would be chosen so as to minimize search time, given the relation between RFR and search time offered by Williams (1967a), and the relation between color difference and RFR shown here. The approach suggested is similar to that used by Kelly (1965) to choose codes of maximum color contrast.

Another application is the choice of shades of gray for search on a black-and-white display. Color difference applies as well to "gray" stimuli as to chromatic stimuli, and would enable a display designer to evaluate whether a black-and-white CRT can produce adequate color difference to provide the level of search performance desired. Of course, greater color difference is available from a color CRT than from a black-and-white CRT. It is interesting to note that color difference for achromatic stimuli is equivalent to indices of brightness contrast, which have long been recognized as a determinant of displayed image quality.

Finally, color difference may apply to search for targets on a continuous background. The results reported here have been for color

difference between discrete targets and discrete background objects. The generalization to a continuous background at least deserves further research, and seems intuitive. For example, search time for a life raft on an ocean should be related to the color difference between the ocean and the raft.

In summary, a physical variable, color difference, has been found which exerts moderate control over two related psychological variables, Relative Fixation Rate (RFR) and search time. Color difference can be calculated for objects varying simultaneously in all three aspects of color, which is an advantage over Williams' (1967a) method of relating RFR to changes of hue or value or chroma. Color difference is suggested to have many applications as a tool for design of search tasks.

CHAPTER 6

EXPERIMENT IV: SPATIAL PATTERN OF TARGET CLASS ITEMS

The preceding experiments in this research project have dealt with displays on which the target class objects were scattered at random. This, of course, need not be the case. Target class items will often form some natural pattern, such as the deployment of forces on a strategic display or the aircraft approach pattern on an air-traffic controller's display. In fact, many of the "random" displays used in the present experiments were probably perceived to be patterned by the observers. In this regard, Feller (1968), the reknowned probabilist, remarked that "to the untrained eye randomness appears as regularity or tendency to cluster" (p. 161).

It is reasonable to ask, then, what is the effect of the pattern of display objects? Smith, Farquhar, and Thomas (1965) studied the effectiveness of color coding on displays having two-digit numbers in a completely filled array of rows and columns. They demonstrated that the structure of the display and the nature of the task interact to determine the effectiveness of the color coding, although color coding was still worthwhile in <u>all</u> tasks studied. Brown and Monk (1975) studied displays with or without statistical constraints on the arrangement of items. The distribution of display items appears "clumpier" on the constrained displays and "lacier" on the unconstrained (random) displays. They found that search times were lower on the constrained displays, and suggested that the finding

reflects the strategy of the subjects. It was suggested that subjects first scan quickly between the clumps of items on the constrained displays and then search through the clumps. This strategy would produce some very fast searches which would lower the average search time for the constrained displays.

Smith, Farquhar, and Thomas (1965) and Brown and Monk (1975) dealt with the pattern of all the display objects. Kahneman (1973), in his chapter on Looking Behavior, discusses the spatial pattern of items to which one is attending (target class objects). He notes that the apparent structure of a display containing many distinct types of items will depend upon which type is the focus of attention. Furthermore, attended items will tend to cluster according to the time-honored gestalt principles: similarity, proximity, common fate, continuity, etc. Color coding provides high similarity among target class items, so those items stand out from the background items. Williams (1967b) and Cahill and Carter (1976) speculate that it is the gestalt made by the target class items which determines the pattern of eye movements in color-coded visual search.

These studies suggest several hypotheses about search when the target class is arranged nonrandomly. The hypothesis of Brown and Monk (1975) that isolated objects are scanned first on patterned displays suggests that target items should be found faster when isolated than when they are in a group of other target class items. The findings of Brown and Monk (1975) and Smith, Farquhar, and Thomas [illegible] indicate that displays having groups of target class items [illegible] gestalt principles should produce faster searches [illegible] the target class items are randomly dispersed.

Experimental Design

Displays of density 60 and TCS 30 were coded with the same colors and frequency of each color as Experiment Ic. However, the target class items in Experiment IV were grouped into sinuous patterns on the basis of proximity and continuity. Four or five target class items were always placed outside the group, while the remaining target class items were in the group. On half of the displays the target was in the group, and on half the displays it was outside the group of target class items. The "in" and "out" displays were matched for target position and other important variables known to affect search time. These 36 displays were searched by 32 subjects who also searched the displays of Experiment V, which were randomly interspersed among these displays.

Results and Discussion

The results of this experiment are considered in two parts: (1) comparison of times for targets "in" or "out" of groups, and (2) comparison of times for displays having grouped target class items with times on random displays that were otherwise identical with the grouped-condition displays.

Mean search time ($\underline{N} = 576$) for targets in the group of target class objects (5.54 sec) was longer than search time for targets outside the group (4.72 sec) ($\underline{F}(1,31) = 9.61$, $\underline{p} < 0.005$). This result is completely consistent with Brown and Monk's (1975) idea that subjects scan outside the group before examining targets in the group. The difference was also significant in log-transformed analysis ($\underline{F}(1,31) = 5.23$, $\underline{p} < 0.03$). No test of the replicability of the

finding was possible because the two matched sets of displays were used to represent targets "in" or "out" of the group on equivalent displays.

Search times obtained in this experiment may be compared with those obtained in the density 60 condition of Experiment Ic ($\underline{N}$ = 648). The displays, colors, color frequencies, and all other display characteristics were exactly the same in these two experiments except that the present experiment had patterned target class items whereas Experiment I had randomly placed items. Mean search time for the targets outside of the pattern of target-colored items (4.72 sec) was significantly shorter than search time for targets on random displays (5.66 sec) as indicated by the Behrens-Fisher statistic ($\underline{t}^* = 3.39$, $\underline{p} < 0.01$). In contrast, there was no significant difference between search time obtained on random displays (5.66 sec) and search time for targets in a pattern of target-colored items (5.54 sec) ($\underline{t}^* = 0.43$).

These results also support the hypothesis of Brown and Monk (1975). Targets inside a pattern are found no more rapidly than targets on a random display. Hence, the shorter average search times for patterned displays are attributable to targets outside of the pattern, as would be expected from the hypothesis of Brown and Monk that areas between groups of targets are scanned before the groups are searched.

It seems likely that the results obtained in an experiment of this type would depend on the probabilities that a target would be in or out of a group of target-colored items. These probabilities were each 0.5 in this experiment, but if the probability of a target being

outside the group was sufficiently small, then an observer might not give priority to scanning outside the groups. Such a consideration may limit the generalizability of the present finding (that isolated targets are found most rapidly).

To summarize: Target class items on a display can be distributed in a pattern or at random. When they are distributed in a pattern, the target can be in or out of the pattern. If the target is <u>out</u> of the pattern, it is found faster than when it is <u>in</u> the pattern or when it is on a random display. If the target is <u>in</u> the pattern, it is found no faster than when it is on a random display which is otherwise identical to the patterned display. It is expected that this effect of rapid searches for targets outside a pattern would become less pronounced as the likelihood becomes smaller that a target would be outside the pattern of the target class items on a display. This would reflect a change of the observer's strategy.

CHAPTER 7

ITEMS ADJOINING THE TARGET

There are numerous reports that perception of visual targets and, in particular, location of search targets is impaired by display items (neighbors) adjoining the target. Many of these reports were described in the Literature Review section. The purpose of this chapter is to present and discuss evidence from the present research which is related to the effect of the target's neighbors.

One of the most provocative suggestions about the effect of neighbors is due to Monk and Brown (1975). They surmise that the well-known effect of display density (e.g., Smith, 1962) may be an artifact of the number of neighbors. Monk and Brown have shown that search time increases with the number of dots neighboring a double-dot target. They reasoned that when display density increases, the number of items neighboring the target also tends to increase. Hence, the possible effect of neighbors and the possible effect of density may be confounded. The present research is unique in that it independently varies display density and the number of items adjoining the target. An effect of one of these variables cannot be an artifact of the other in this case. In Experiment I, for example, a significant effect ($\underline{F}(1,51) = 19.47$, $\underline{p} < 0.01$) of display density is found even though the number of items neighboring the target is controlled. Therefore, the effect of display density

cannot be an artifact of the target's neighbors in that experiment.

Experiments Ia, Ib, Ic, IIb, and IIc were examined in order to discover whether neighbors or their interaction with other variables had significant effects on search for color-coded numbers. These experiments were chosen because they provide large numbers of subjects (18 in each of the five experiments) so that relatively high statistical power can be achieved by accumulating an effect across subjects. Experiment IIa is not included because it represents an unusual condition with no background items, neighbors or otherwise.

Experiments I (a, b, and c) and II (b and c) controlled the number of neighbors in a factorial arrangement with TCS, target proximity to the edge of the display (Edge), target placement in the upper or lower half of the display (Upper-Lower), display density, and replication of the experiment with random choice of uncontrolled variables. Each experiment gives rise to 16 effects involving neighbors, not including replication. If all of these effects were tested at the 0.95 confidence level, then at least one Type I statistical error in each experiment would be likely! In order to investigate the effect of neighbors in these experiments, yet retain some control on the error rate of the statistical tests, the following data analysis strategy was adopted. The only effects investigated further were those which were statistically significant in both raw-score and log-transformed analyses and which did not change significantly upon replication. This procedure produces Type I error rates of less than 0.05 per experiment. The

requirement of replication is some insurance that an effect is not due to some uncontrolled facet of the displays. The requirement that the effect be significant in both raw-score and log-transformed analyses is in keeping with Smith's (1963) suggestion that doing both kinds of analyses is more informative than doing one or the other. The log-transformed analysis forces the data into a form which more nearly meets the statistical assumptions of Analysis of Variance, but it is based on meaningless units (log seconds). The raw-score analysis retains meaningful units, but is less tenable because it violates an assumption of Analysis of Variance (i.e., homogeneity of variance). The requirement that both analyses be significant provides the advantages of each at the expense of some statistical power.

Reanalysis of Experiments I and II

Table 7 lists all effects in Experiment I (a, b, and c) which include neighbors, and shows statistical tests of these effects in raw-score and log-transformed data. If either of the tests is significant ($p < 0.05$), then a test for possible change of the effect upon replication is also presented. A significant test for replication indicates that the preceding effect changed noticeably when the experiment was repeated with the same subjects in the same sitting. Such significant but changeable effects are best regarded as "noise." For example, the main effect of neighbors is statistically significant ($p < 0.01$) in both log and raw analyses, yet it changes ($p < 0.01$) when the experiment is repeated with new displays representing the

Table 7

Analysis of Variance for Sources Involving Neighbors

in Experiment I

Source	df	MS	df_{err}	F	MS_{log}	F_{log}
Neighbors (N)	2	47.01	102	6.37**	0.31	7.13**
Replication[a]	2	36.53	102	7.20**	0.81	19.03**
N X TCS (T)	4	35.19	102	4.77**	0.15	3.41*
Replication	4	7.52	102	1.48	0.19	4.56**
N X Density (D)	2	3.33	102	0.39	0.04	0.79
N X D X T	4	3.44	102	0.40	0.08	1.49
N X Edge (E)	4	2.57	204	0.27	0.17	2.88**
Replication	4	28.13	204	3.17*	0.22	4.17**
N X E X T	8	2.54	204	0.26	0.08	1.42
N X D X E	4	58.01	204	7.28**	0.34	6.98**
Replication	4	7.90	204	1.32	0.16	3.75**
N X D X E X T	8	48.82	204	6.13**	0.28	5.76**
Replication	8	6.51	204	1.09	0.01	0.36
N X Upper-Lower (U)	2	14.16	102	2.58	0.12	2.30
N X U X T	4	8.99	102	1.64	0.09	1.63
N X U X D	2	25.92	102	6.70*	0.07	1.62
Replication	2	47.42	102	6.63**	0.34	6.43**
N X U X D X T	4	34.57	102	8.94**	0.13	3.13*
Replication	4	37.40	102	5.23**	0.15	2.88**
N X E X U	4	25.84	204	3.61**	0.09	1.91
Replication	4	16.38	204	2.27	0.07	1.53
N X E X U X T	8	17.60	204	2.46*	0.04	0.36
Replication	8	13.55	204	1.88	0.15	2.99**
N X D X E X U	4	31.74	204	4.90**	0.25	5.29**
Replication	4	19.41	204	2.75*	0.14	2.89*

Table 7 (Continued)

Source	df	MS	df_{err}	F	MS_{log}	F_{log}
N X D X E X U X T	8	14.89	204	2.30*	0.09	1.84
Replication	8	14.21	204	2.01*	0.07	1.60

[a]Replication means the interaction of the preceding effect with a randomly generated repetition of the experiment.

* $p < .05$

** $p < .01$

same conditions. Table 8 shows this interaction of the number of items neighboring the target and repetition of the experiment.

Only one effect in Table 7 is significant in both analyses, and does not change significantly on replication: the interaction of neighbors, density, proximity of the target to the edge, and TCS. This interaction is shown in Table 9. The number of neighbors had little effect unless TCS was 30. In that case, search time increased as the number of neighbors increased (when display density was 30) unless the target was in the center of the display. This effect is too complicated to be of much theoretical or practical value. Overall, this analysis indicated that the number of items adjoining the target has no interpretable effect on search times when the targets are color-coded numbers. This conclusion was verified by examining the results of Experiment II (b and C) with respect to the effect of neighbors.

Remember that in Experiment IIb the target items were adjoined by items of a color similar to that of the target, and Experiment IIc was like IIb except that the additional items were dissimilar to the target. Once again, it was required that both raw-score and log-transformed analyses produce significant ($\underline{p} < 0.05$) tests of an effect, and that the effect be replicable before the effect was given further consideration. This strategy was intended to cope with the multiplicity problem, and with the problem of whether to analyze search times in transformed or untransformed state. Table 10 shows the Analysis of Variance for all effects in Experiment II (b and c) having as a component the number of items neighboring the target. One

Table 8

Effect of the Number of Items in the Neighborhood of the Target

	Number of Neighbors		
	0	1	2
Replication 1	2.79[a]	2.95	2.90
Replication 2	2.76	2.82	3.39

[a]Mean search time in seconds (N = 648).

Table 9

Interaction of Neighbors, Density, Target Eccentricity, and TCS

Display Density	TCS	Number of Neighbors 0	1	2
Target Eccentricity: Near Center of Display				
30	30	5.22[a]	5.92	4.70
	10	2.09	2.94	2.56
	1	0.98	0.84	0.83
60	30	5.85	5.59	8.48
	10	3.17	2.39	2.63
	1	1.04	1.02	1.08
Target Eccentricity: Between Center of Display and Edge				
30	30	3.66	4.11	5.68
	10	2.30	2.05	2.24
	1	0.93	0.85	0.99
60	30	5.01	6.15	5.11
	10	2.55	3.03	2.92
	1	0.80	0.75	1.22
Target Eccentricity: Near Edge of Display				
30	30	3.87	4.28	5.93
	10	2.15	2.06	2.60
	1	1.19	1.07	1.06

Table 9 (Continued)

Display Density	TCS	Number of Neighbors 0	1	2
60	30	5.03	4.86	4.87
	10	2.96	3.04	2.63
	1	1.14	1.02	1.10

[a]Mean search time in seconds ($\underline{N}$ = 72).

Table 10

Analysis of Variance for Sources Involving Neighbors

in Experiment II

Source	$\underline{df}$	$\underline{MS}$	$\underline{df}_{err}$	$\underline{F}$	$\underline{MS}_{log}$	$\underline{F}_{log}$
Neighbors (N)	2	24.12	68	3.12	0.24	5.48**
Replication[a]	2	0.12	68	0.01	0.06	0.85
N X Similarity (S)	2	10.38	68	1.34	0.20	4.61**
Replication	2	1.83	68	0.14	0.03	0.44
N X TCS (T)	2	40.06	68	4.65*	0.34	6.70**
Replication	2	1.16	68	0.08	0.02	0.20
N X T X S	2	0.18	68	0.02	0.02	0.37
N X Edge (E)	4	16.38	136	1.57	0.02	0.34
N X E X S	4	13.64	136	1.31	0.08	1.62
N X E X T	4	21.58	136	2.05	0.05	0.94
N X E X T X S	4	12.89	136	1.22	0.08	1.40
N X Upper-Lower (U)	2	116.35	68	11.97**	0.84	18.47**
Replication	2	14.63	68	1.22	0.03	0.59
N X U X S	2	10.93	68	1.12	0.10	2.28
N X U X T	2	133.70	68	12.83**	1.19	22.98**
Replication	2	15.90	68	1.44	0.03	0.59
N X U X T X S	2	9.43	68	0.91	0.00	0.09
N X U X E	4	90.65	136	10.22**	0.56	12.38**
Replication	4	35.63	136	3.23*	0.16	2.77*
N X U X E X S	4	8.00	136	0.91	0.09	1.94
N X U X E X T	4	75.09	136	8.44**	0.35	7.32**
Replication	4	26.11	136	2.29	0.09	1.39
N X U X E X T X S	4	7.04	136	0.79	0.04	0.86

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Table 10 (Continued)

[a] Replication means interaction of the preceding effect with a randomly generated repetition of the experiment.

* $p < .05$

** $p < .01$

four-way interaction: neighbors by target proximity to the display edge by placement in the upper or lower half of the display by TCS, and three of its components meet the criteria for further consideration. This four-way interaction is listed in Table 11.

The interaction shows several similarities to the interaction found in the analysis of "neighbors" effects in Experiment I. For example, search times were more variable when TCS was larger. This heterogeneity of variance was the main reason that the search times were log transformed for one of the analyses. The significance of these interactions in the analysis of transformed times suggests that increased variability when TCS was large was not the sole source of these effects. Another aspect in common between the results of Experiments I and II is that the most unexpected pattern of results occurred in the center of the display. Specifically, when TCS is 30 the search time for the lower half is unexpectedly short, and for the upper half of the display the time is surprisingly long in Experiment II. The unusually long searches for density 30, TCS 30 also occur in the center of the display in both Experiments I and II.

None of the results which were common to Experiments I and II signify any interpretable effect of the number of items adjoining the target. However, an additional possibility is considered: perhaps the neighbors must be similar to the target in order to interfere with search. This was certainly the case in Monk and Brown's (1975) experiment with search for double-dot targets embedded among single dots.

Table 11

Interaction of Neighbors, TCS, and Target Position

		Number of Neighbors		
Upper or Lower Half	TCS	0	1	2
Target Eccentricity: Near Center of Display				
Upper	1	0.79[a]	0.94	0.79
	30	6.30	4.08	4.88
Lower	1	0.93	0.96	1.05
	30	3.61	6.20	5.44
Target Eccentricity: Between Center and Edge				
Upper	1	0.85	1.15	1.00
	30	4.04	4.42	4.21
Lower	1	1.00	1.09	1.11
	30	5.84	4.91	5.14
Target Eccentricity: Near Edge				
Upper	1	1.06	1.05	5.15
	30	5.41	3.90	4.92
Lower	1	1.17	1.36	1.53
	30	4.42	5.26	5.61

[a]Mean search time in seconds ($\underline{N}$ = 72).

Experiment V

Another experiment (V) was conducted because objects adjoining a target may interfere with and reduce the latency of responses to the target to the extent that the adjoining objects are like the target (e.g., Bjork & Murray, 1977). On the basis of this, one might predict that items neighboring targets would effect search time, although the direction of the effect is uncertain. Search time may increase because of the interference with perception, or search time may decrease if the reduction of response latency has a stronger effect. In order to investigate these possibilities, displays with density 30, TCS 20, and either 2 or 0 items neighboring the target were searched by two groups of 16 subjects. One group saw the displays coded with colors assigned to display items at random, except that items neighboring the target were of the target's color. The second group saw the same displays with the target adjoined by items of high color contrast with the target. Both groups viewed the 24 displays of this experiment interspersed at random with the 36 displays of Experiment IV in which colors adjoining the targets were assigned at random.

The results of the experiment are shown in Table 12. The HSD statistic (Kirk, 1968) is provided to enable the reader to make comparisons of means in the four cells of the table. The HSD indicates that the absence of neighboring items affected search time only when the target and its neighbors were of the same color (an interaction). An Analysis of Variance of the data of Table 12 is presented in Table 13. The Analysis of Variance tests imply, on the contrary,

Table 12

Effect of Color Contrast of the Target and Its Neighbors

	No Neighbors		Two Neighbors
Same Color (Group 1)	3.26[a]	0.74*	4.00
		0.80*	
Contrasting Color (Group 2)	3.80		4.06

[a]Mean search time in seconds ($\underline{N}$ = 192).

* $HSD_{.05} = 0.62$

Table 13

Analysis of Variance for Color Contrast of Targets and Neighbors

Source	df	MS	df_{err}	F	MS_{log}	F_{log}
Neighbors (N) (0 versus 2)	1	49.13	30	9.72**	0.87	3.53
Replication[a]	1	7.10	30	1.19	0.02	0.27
Color Contrast of Target and Neighbors (C) (same color versus contrasting colors)	1	17.16	30	1.34	0.55	16.46**
Replication	1	6.75	30	0.92	0.08	1.44
N X C	1	10.93	30	2.16	0.02	0.31
Replication	1	1.05	30	0.18	0.02	0.37

[a]Replication means interaction of the preceding effect with a randomly generated repetition of the experiment.

** $p < .01$

that there was no interaction of color contrast and the number of neighbors. There is also conflicting evidence in the Analysis of Variance about which main effect was operating here. Analysis of raw scores indicates an effect of the number of neighbors only, and analysis of log-transformed scores indicates an effect of color contrast only. Apparently, there was <u>some</u> effect related to the number of neighbors and their color. Unfortunately, the effect is uninterpretable in terms of neighbors. Furthermore, there is no evidence that the effect was different upon replication of the experiment.

In summary, the effect of items neighboring the target was sought in three experiments including 122 subjects who made 4,248 searches of displays representing varied numbers (0 through 2) of items adjoining the target (neighbors). The number of neighbors had no replicable main effect in these experiments, nor any interaction which generalized across experiments. An attempt to demonstrate an effect of neighbors of the same color as the target also gave equivocal results.

Nonetheless, under certain conditions there were large and apparently replicable changes of mean search time. However, these changes were not clearly associated with the variables controlled by these experiments. Perhaps the changes should be attributed to the inherent unreliability of search times, or perhaps the number of items neighboring the target interacts with some variable not controlled in this research. Overall, there was no consistent or convincing evidence of an effect of items neighboring the target. The

previous finding by Monk and Brown (1975) of such an effect may have been due to the type of search targets they used (double dots among single dots). Anyway, the effect did not generalize to color-coded numbers.

CHAPTER 8

TARGET POSITION

If subjects' search patterns were random, then average search time would be the same for targets at all positions on the displays. On the contrary, the Literature Review section cites evidence that targets at some positions on displays are found faster than at other positions. For instance, targets tend to be found faster in the top half of a display than in the bottom half (e.g., Gordon & Winwood, 1973). It has also been found that search times are shorter for targets near the center of a display than for those near its outer edge (e.g., Baker, Morris, & Steedman, 1960). These effects may reflect a stereotypic search strategy, or they may reflect some characteristic of certain positions on the display which makes targets more difficult to recognize in those positions. Such questions of search strategy and difficulty of recognition are most directly answered with eye-movement recordings. However, search time experiments like those reported here can be used to test the generality of the position effects. No previous research has been done on the effects of target position on search for color-coded numbers. In this chapter, the effects of target position in Experiments I and II are discussed.

The data analysis strategy used in Chapter 7 was also used here: the only effects considered were those which were statistically

significant ($p < 0.05$) in both raw-score and log-transformed analyses, and which did not change significantly upon replication of the experiment. The rationale for this strategy, which was explained in Chapter 7, is that it affords control over the Type I error rate and it supports both the interpretability of the units and the statistical tenability of tests of effects.

Two position effects controlled in this research were placement of the target in the upper or lower half of the display and the radial position of the target between the center and the outer edge of the display. The former will be called Upper-Lower and the latter will be called Edge. The exact specifications of these position variables were given in Chapter 2 (Methods).

In Experiment I (a, b, and c) none of the effects of target position was significant and replicable in both transformed and nontransformed analyses (see Table 14). The main effect of target proximity to the edge of the display was significant only in the raw-score analysis. The main effect of target placement in the upper or lower half of the display was not replicable, being a 0.4-second change of search time (lower half slower) in one replication and only a 0.1-second change in the other. In Experiment II (b and c) there was a significant four-way interaction of TCS, Edge, Upper-Lower, and the type of background (see Table 15). In this experiment, the main effect of target proximity to the edge of the display was significant only in the log-transformed analysis. The main effect of target placement in the upper or lower half of the display was statistically significant in both analyses and was

Table 14

Analysis of Variance for Sources Involving Target Position

in Experiment I

Source	df	MS	df_{err}	F	MS_{log}	F_{log}
Edge (E)	2	60.65	102	5.34**	0.14	1.92
Replication[a]	2	10.05	102	1.36	0.12	2.80
Upper-Lower (U)	1	67.34	51	5.25*	1.21	7.50**
Replication	1	20.42	51	5.00*	0.25	5.60*
E X U	2	6.84	102	0.84	0.02	0.41
E X TCS (T)	4	57.56	102	5.06**	0.39	5.50**
Replication	4	40.54	102	5.50**	0.32	7.33**
U X T	2	32.32	51	2.52	0.61	3.80*
Replication	2	13.24	51	3.24*	0.05	1.18
E X Density (D)	2	8.49	102	0.92	0.03	0.61
U X D	1	96.67	51	9.60**	0.50	9.65**
Replication	1	58.40	51	14.42**	0.26	5.53*
E X T X D	4	17.21	102	1.86	0.22	4.13**
Replication	4	24.03	102	3.75**	0.16	2.44*
U X T X D	2	55.09	51	5.47**	0.31	5.93**
Replication	2	77.55	51	19.15**	0.49	10.61**
E X U X T	4	16.37	102	2.01	0.07	1.23
E X U X D	2	78.18	102	9.96**	0.68	11.63**
Replication	2	16.25	102	3.03	0.19	4.63*
E X U X T X D	4	37.01	102	4.72**	0.06	1.02
Replication	4	16.04	102	2.99*	0.10	2.39

[a]Replication means interaction of the preceding effect with a randomly generated repetition of the experiment.

* $p < .05$

** $p < .01$

Table 15

Analysis of Variance for Sources Involving Target Position in Experiment II

Source	df	MS	df_{err}	F	MS_{log}	F_{log}
Edge (E)	2	9.66	102	0.83	0.83	11.56**
Replication[a]	2	1.73	102	0.22	0.02	0.44
Upper-Lower (U)	1	97.59	51	6.85*	2.44	13.88**
Replication	1	3.91	51	0.37	0.08	1.36
E X U	2	20.34	102	1.79	0.02	0.26
E X TCS (T)	2	23.31	102	2.35	0.20	4.02*
Replication	2	2.72	102	0.34	0.04	0.90
U X T	1	24.45	51	2.43	0.40	6.18*
Replication	1	0.68	51	0.06	0.00	0.01
E X Background (B)	4	47.04	102	4.04**	0.59	8.23**
Replication	4	10.22	102	1.29	0.02	0.33
U X B	2	5.71	51	0.40	0.25	1.39
E X T X B	4	21.90	102	2.21	0.19	3.80**
Replication	4	9.78	102	1.22	0.02	0.50
U X T X B	2	24.70	51	2.45	0.48	7.43**
Replication	2	20.26	51	1.67	0.22	3.05
E X U X T	2	29.74	102	2.82	0.08	1.63
E X U X B	4	41.85	102	3.69**	0.15	2.32
Replication	4	5.17	102	0.52	0.07	1.36
E X U X T X B	4	65.34	102	6.19**	0.35	7.38**
Replication	4	3.07	102	0.32	0.05	1.19

[a]Replication means interaction of the preceding effect with a randomly generated repetition of the experiment.

* $p < .05$

** $p < .01$

replicable (a 0.32-second slowing of searches for targets in the lower half of the display). Also significant and replicable in log and raw-score analyses was an interaction of proximity to the edge and the type of background. This interaction is a component of the significant four-way interaction listed in Table 16. This interaction has several salient features. When TCS was 30, the search times were quite variable, and show no meaningful pattern. When TCS was 1, the search times were unaffected by target position on displays containing target-colored items alone or with very dissimilar background items. However, when the background was similar to the target color, search times were consistently longer in the lower half of the display and became longer as the target approached the outer edge of the display. If it is assumed that the targets are recognized by comparative judgment when the background items are of a color similar to that of the target, then this interaction is to be expected. A target near an edge has few nearby display items to compare with it, so it is more difficult to recognize when the background items are very similar to the target color. When the background items are very dissimilar, this comparison is not necessary, so that a lack of nearby items at an edge does not slow search.

It seems, then, that target position affected search only under the special circumstance of a small Target Class Size and background items which were similar to the target. This condition is so restrictive that these conclusions must be regarded as tentative. However, it is clear that there is no noteworthy general effect of target placement in the upper or lower half of a display or of target

Table 16

Interaction of Target Position, TCS, and Background Condition in Experiment II

Upper or Lower Half	TCS	Background Condition[a] 0	1	2
Target Eccentricity: Near Center of Display				
Upper	1	0.49[b]	0.60	1.43
	30	4.71	4.87	5.67
Lower	1	0.51	0.63	1.80
	30	5.26	4.13	5.86
Target Eccentricity: Between Center and Edge				
Upper	1	0.50	0.63	1.87
	30	3.87	4.31	4.50
Lower	1	0.51	0.62	2.08
	30	3.88	5.66	6.34
Target Eccentricity: Near Edge of Display				
Upper	1	0.55	0.63	2.08
	30	3.47	3.96	6.80
Lower	1	0.54	0.62	2.89
	30	5.49	4.38	5.42

Table 16 (Continued)

[a]Background conditions: 0 = no background items, 1 = background items dissimilar to targets, 2 = background items similar to targets.

[b]Mean search time in seconds (N = 72).

eccentricity on the display. This conclusion is contrary to those reached by other investigators, who used "dot" or "blip" targets (e.g., Baker, Morris, & Steedman, 1960).

One might argue that conclusions based on colored displays and mean search times should not be compared with those of Baker, Morris, and Steedman (1960) which were based on black-and-white displays and median search times. In anticipation of such criticism, statistical inference was done on median search times obtained with the black-and-white displays of this research. Baker, Morris, and Steedman found that search time increased by 30% at the outer edge of the display, compared with median search time near the center. On the contrary, results from the present research show a statistically significant decrease of median search times at the outer edge of a black-and-white display (Friedman test, chi-squared (2) = 8.41, $p < 0.02$). Median search times (in seconds) within 1.5° of the outer edge, within 3° of the center, and in the intermediate 2.5° were 4.47, 5.35, and 4.77, respectively. The median time for the center was significantly ($p < 0.05$) longer than the other two by multiple comparisons associated with the Friedman test. No other differences were significant. Furthermore, the Kendall coefficient of concordance ($K = 0.0097$) indicates that the significant difference between search times in the center 6° disc and in the remainder of the display was not regularly obtained for all combinations of other display conditions.

The contradiction between these results and those of Baker, Morris, and Steedman (1960) may simply be due to the difference

between the "blip" targets they used and the numerical targets used here. It is suspected, however, that the results obtained for target placement on black-and-white displays in this research are irreplicable. This suspicion is supported by the lack of concordance of results obtained when the target eccentricity is varied in association with other display conditions. These "phantom" effects of target eccentricity were sometimes found to be statistically significant but were generally irreplicable in this research with color-coded displays.

In summary, two target-position variables were expected to affect search time. The variables are placement in the top or bottom half of the display and radial position of the target between the center and the outer edge of the display. Neither of these variables was found to affect search time in a repeatable manner. Target placement in the top half of the display resulted in significant but changeable reduction of search times in one family of experiments, and had an unchanging effect in another family of experiments. The target eccentricity on the display had no repeatable effect, except some uninterpretable four-way interactions which were different in different experiments. The direction of the effect found in this research for target eccentricity on black-and-white displays is contrary to the direction found by other investigators. Such an inconsistent effect, even if it occasionally reaches statistical significance, is best interpreted as no effect.

CHAPTER 9

INDIVIDUAL DIFFERENCES

One of the most consistent causes of variability of search times is differences among the people who do the searching; some people are faster searchers than others. A sample of 78 people (four experiments) in this research were studied in detail in an attempt to discover why some people are faster searchers than others. Fortunately, there is evidence of individual differences in mean search time for each of the four experiments in the sample; the tests for differences among the means for subjects in each of the four experiments yielded the following $\underline{F}$ ratios: $\underline{F}(17,17) = 6.47$, $\underline{p} < 0.01$; $\underline{F}(17,17) = 2.32$, $\underline{p} < 0.05$; $\underline{F}(17,17) = 2.43$, $\underline{p} < 0.05$; and $\underline{F}(23,92) = 4.66$, $\underline{p} < 0.01$.

Mean search times for each subject were calculated to represent individual search speed. The mean is the measure which is usually tested in the significant statistical tests for individual differences. However, these means and their variances are different in each of the four experiments. Hence, normal ($\underline{Z}$) scores of the means were calculated in each experiment to make the means comparable across experiments. The correlations of $\underline{Z}$ scores with raw means ranged from 0.90 to 0.96, indicating that the $\underline{Z}$ scores are an excellent representation of the original distribution of search-time means. These $\underline{Z}$ scores, then, were the criterion to be predicted by

several individual difference characteristics which were suggested in the literature review to be related to search speed.

Individual Characteristics

General Characteristics

Some general characteristics of the subjects which may be related to search speed are age, sex, and recent consumption of drugs or alcohol. Sex of each subject was recorded as observed by the experimenter (0 = female, 1 = male). Women constituted 56.4 percent of the sample. Age and recent drug or alcohol consumption (0 = none, 1 = some) were based on the subjects' responses to inquiries. The ages in years (and the percentage of subjects of each age in the sample) were, respectively, 17 (5.1), 18 (30.8), 19 (28.2), 20 (20.5), 21 (3.8), 22 (1.3), 24 (1.3), 25 (3.8), and 31 (1.3). Drugs or alcohol had been consumed in the preceding 24 hours by 33.3 percent of the sample.

Johnston (1966) showed that smokers produce slower searches than nonsmokers. Subjects in the present experiment were asked whether they smoked and their replies were recorded (0 = no, 1 = yes). Only 16.7 percent of the subjects were smokers.

Reading Speed

Boynton (1960) suggested that reading speed might be related to search speed. A test of reading speed was devised in order to test this suggestion. Subjects were asked to read a one-page passage from

a textbook to find the answer to a single question given before the reading began. The question was an interogative reformulation of a statement in the passage. The subject's reading speed score was the duration from the time he looked down to the page until he looked up to give the answer to the question (and to point to the answer in the text). Three passages were read. The first passage was for practice, and the remaining two passages provided for calculation of test-retest reliability. The reliability was 0.72 (n = 78). The two scores for each subject were added and the reliability of the combined score was estimated to be 0.84. The distribution of reading times was approximately symmetrical with a mean of 40.7 seconds and a standard deviation of 17.7 seconds. Longer reading time indicates slower reading speed.

Parafoveal Acuity

The results of Erickson (1964) indicated that search speed should be related to a subject's ability to resolve detail in averted vision (parafoveal acuity). A circle-square acuity test (Westheimer, 1972) was devised to measure parafoveal acuity. The subject's task in this test was to say which shape (circle or square) had been flashed (0.1 sec) at one side or the other (right or left at random and unannounced to the subject) of a fixation point. The shapes were presented 1.7°, 2.4°, 3.0°, and 4.0° from the subject's line of sight in four sessions in random order.

The luminance of the shapes was 40 mL and the luminance of the background was 0.48 mL. The test materials were 45 inches (1.14

meters) from the subject's eyes. The psychophysical procedure used was a Wetherill and Levitt (1965) staircase which produced a 71% threshold. Six ascending or descending trials were included in the estimated threshold for each subject at each eccentricity.

Reliability of a subject's score at any of the four eccentricities was estimated by the coefficient of generalizability (Cronbach, Gleser, Nanda, & Rajaratnam, 1972). Subjects were considered a random effect, and eccentricity and trial number at each eccentricity were fixed effects. The coefficient of generalizability ($\underline{r}^2$) was 0.89, and the reliability ($\underline{r}$) was estimated to be 0.94. The average acuity scores at eccentricities of 1.7°, 2.4°, 3.0°, and 4.0° were 3.3, 4.2, 5.2, and 6.1, respectively. Each unit of this score corresponded to a change of about 0.5 minutes of the minimum separandum, and a score of 5.2 corresponded to a separandum of about 6 minutes of arc.

Foveal and Stereo Acuity

Foveal and stereo acuity were measured with a Titmus vision tester. The stereo acuity test was intended as an omnibus test of visual health because it reflects many visual factors which must function correctly to provide stereoscopic vision. Foveal acuity was measured to complement measurements of parafoveal acuity, even though it has never been found to be related to search speed.

Thirty-seven percent of the subjects were able to discern correctly the smallest targets of the Titmus near acuity test (score 14 on a scale from 0 to 14). Only three subjects were unable to see

targets large enough to achieve a score beyond 9, which was the poorest score. (A score of 10 is equivalent to the 20/20 standard.)

Stereo acuity scores had a bimodal distribution with modes at 9 and at 3 (on a scale from 0 to 9). Two subjects could not even pass the easiest example, so this test provided a wide range of scores.

Color Vision

The Hardy, Rand, and Rittler pseudoisochromatic plates were used to test color vision. All but three subjects passed the screening plates (Score 4). One was classed by the plates as having a severe color deficiency (Score 1), and two were classed as having moderate deficiencies (Score 2).

Relation of Individual Characteristics to Search Speed

None of the personal characteristics were related to search speed. Correlations of the individual difference variables with normal scores of average search speed are shown in Table 17. (A matrix of correlations among all these variables is presented in Appendix C.)

Although only two of the coefficients had an unexpected sign (smokers and acuity 1.7°), none of the correlations were statistically significant. Furthermore, no combination of these personal characteristics yielded a significant regression equation. The best equation, in terms of maximizing the F ratio, included two terms: acuity at 4° and foveal acuity ($F(2,76) = 2.95$, $p > 0.05$, $R = 0.27$).

Table 17

Correlations Between Search Time and Personal Characteristics

($\underline{N}$ = 78)[a]

Characteristic	Product-Moment Correlation
Sex (0 = female, 1 = male)	0.14
Smoking (0 = no, 1 = yes)	-0.05
Age (years)	-0.11
Drug or Alcohol Use in Past 24 Hours (0 = no, 1 = yes)	-0.06
Acuity	
Foveal (0 = poor, 14 = excellent)	-0.19
1.7° (1 = excellent, 10 = poor)	-0.04
2.4° (1 = excellent, 10 = poor)	0.04
3.0° (1 = excellent, 10 = poor)	0.08
4.0° (1 = excellent, 10 = poor)	0.21
Reading Speed (lower numbers = faster)	0.09
Stereo Acuity (0 = poor, 10 = excellent)	-0.09
Color Vision (1 = poor, 4 = normal)	-0.16

[a]Critical value of $\underline{r}(78)$, $\underline{p} < 0.05$ is 0.22 (for two-tailed tests).

It is intriguing, however, that Erickson (1964) also found that acuity at 4° was a better predictor of search speed than acuity at any other eccentricity.

There are several possible reasons why the individual difference variables failed to predict the differences in search time for these subjects. One possibility is that the characteristics are not really related to search speed. None of them have a very strong evidence in their favor on the basis of the literature review, although some (e.g., reading speed and parafoveal acuity) have a compelling commonsense appeal as predictors of search speed.

The acuity measures may have failed because they did not include the effects of the background objects. Engel (1977) has shown that the eccentricity at which a target can be seen depends on the background, so perhaps parafoveal acuity measurements should be made with background clutter like that on the search displays for which search time is to be predicted.

A third possibility is that the normal score transformation of the search times distorted the data so that the relationships between search times and other variables were obscured by the transformation. It could be argued that the original search time data were highly skewed, so that normal scores would not be adequate to represent the raw data. However, there is evidence that this argument has little merit. For example, median search times for each subject (rather than mean search times) were also unrelated to the individual difference variables. Median search time tends to be distributed more normally than mean search time because medians are insensitive

to occasional extremely prolonged searches which produce skew in the search time distribution. Despite this, normal scores of median search times had lower correlations with the individual difference variables than did mean search times. In addition, the mean search times each included 72 observations so that the distribution of the means tended to converge to normal even though the individual search times were not normally distributed. Finally, the normal score transformation was not the source of the unrelatedness of search times and individual difference variables because they were not significantly related before the transformation in any of the four experiments from which the sample of subjects was drawn.

A fourth possible reason for the lack of a demonstrable relation between search time and individual differences is unreliability of search time scores. High reliability of some of the predictor scores has already been noted. The search time means for the subjects had coefficients of generalizability (Cronbach et al., 1972) ranging from 0.94 to .99 in the four experiments sampled for this study of individual differences. This coefficient represents generalization of subject's mean scores (with 72 observations per mean) across repetitions of the same experiment. Hence, unreliability of the mean search times was not a primary cause of the low correlations of search time with individual difference tests.

In summary, the only tenable reason for low correlations of search time and the individual difference measures is that the characteristics they represent are, at best, only weakly related to

search speed. The consistent findings of significant individual differences of search speed are a result of some personal characteristics not represented by the variables of this investigation.

CHAPTER 10

EFFECTS OF EXPERIENCE WITH THE SEARCH TASK

It might be expected that subjects' scores would improve during the sequence of 72 searches in Experiments I (a, b, d) and II (a, b, c). Each of these six experiments employed a separate group of 18 subjects. Prior to viewing the 72 experimental displays, subjects were given a single orientation trial in Experiment I, and were given four orientation trials in Experiment II.

Data from Experiments I (a, b, d) and II (a, b, c) were originally analyzed to find effects of Target Class Size, the number of background items, and other variables of primary interest. The 72 search displays were put in a different random order for each subject so that effects of the variables of primary interest would not be confounded with the effects of practice. Conversely, the randomization also makes possible an analysis of the effects of practice, unconfounded with effects of other variables.

Experimental Design

The 72-trial sequence was composed of two random replications of 36 displays representing a factorial arrangement of display density, target position, and the number of objects adjoining the target. Each of these two replications was equally often first to be searched. The order of the 36 displays was the same in the two

replications for any subject, and that order was determined at random for each subject. The 36 trials in each replication were assembled, for purposes of analysis of practice effects, into six blocks of six trials. Hence, the experimental design provided for an analysis of the 72 trials of practice into a factorial arrangement of six trials within each of six blocks within two halves of the experiment within each of six experiments.

Results and Discussion

Of course, the experiment (Ia, Ib, Id; IIa, IIb, or IIc) had an effect on search times ($F(5,102) = 130$, $p < 0.001$). Heterogeneity of the variances and covariances of within-subjects effects was found (chi-squared (2555) = 3041.8, $p < 0.001$), so that the Box-Geisser-Greenhouse conservative F test was computed for within-subjects effects (Games & Klare, 1967). None of the within-subjects effects, halves, blocks, or trials, were significant at any reasonable confidence level for nontransformed data. The noneffect of practice is depicted in Figure 6. However, a log transformation, which is commonly used for search time data (Smith, 1963), produced a significant conservative F test for interaction of experiments and halves of experiments ($F(5,102) = 4.80$, $p < 0.001$). Antilogs of the mean log search times are geometric mean search times, which are plotted for each half of each experiment in Figure 7.

The most salient aspect of the interaction depicted in Figure 7 is that search times increased with practice in Experiment Id (black-and-white displays) and decreased with practice in all other

Figure 6. Mean Search Time Versus Trials of Search Practice.

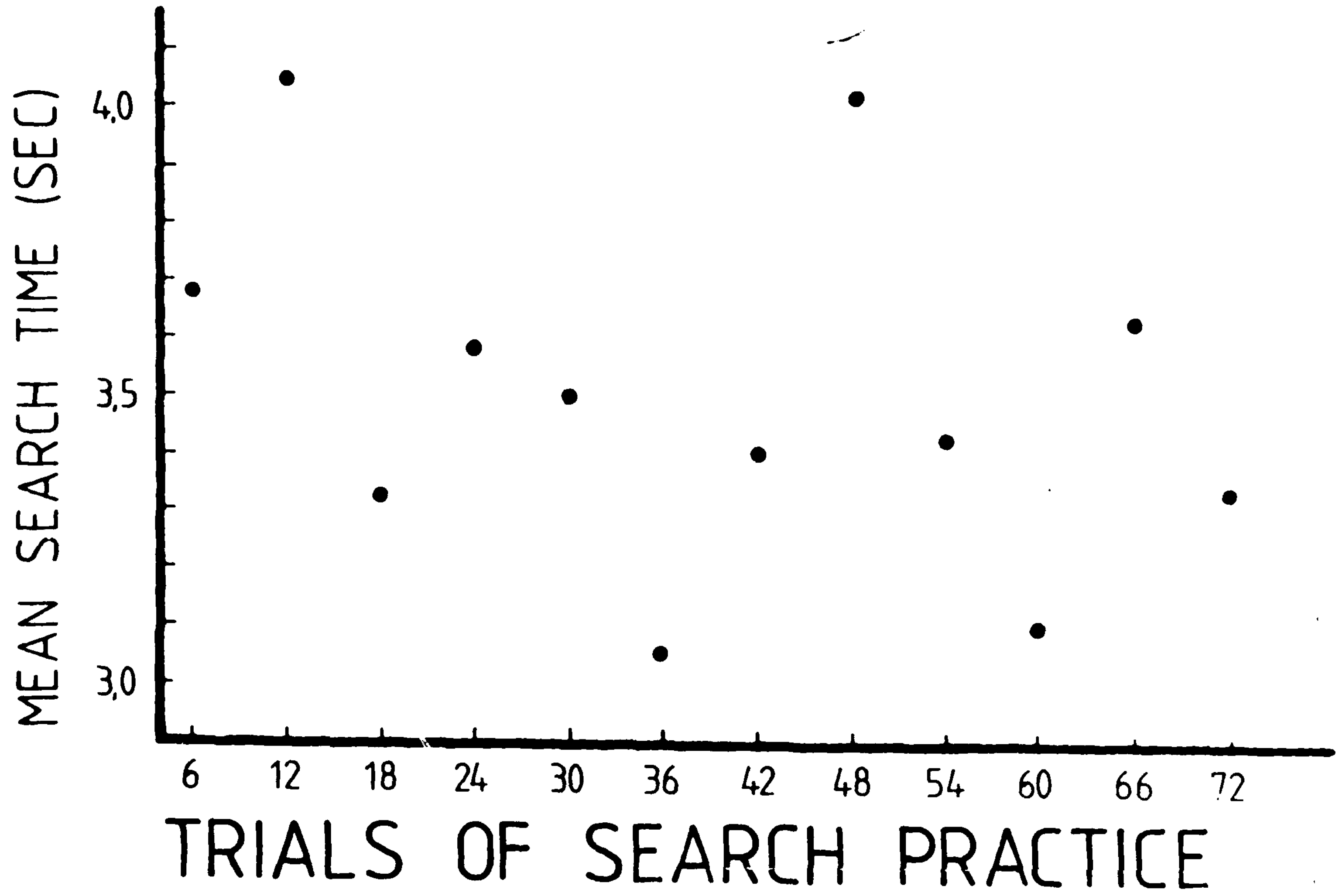
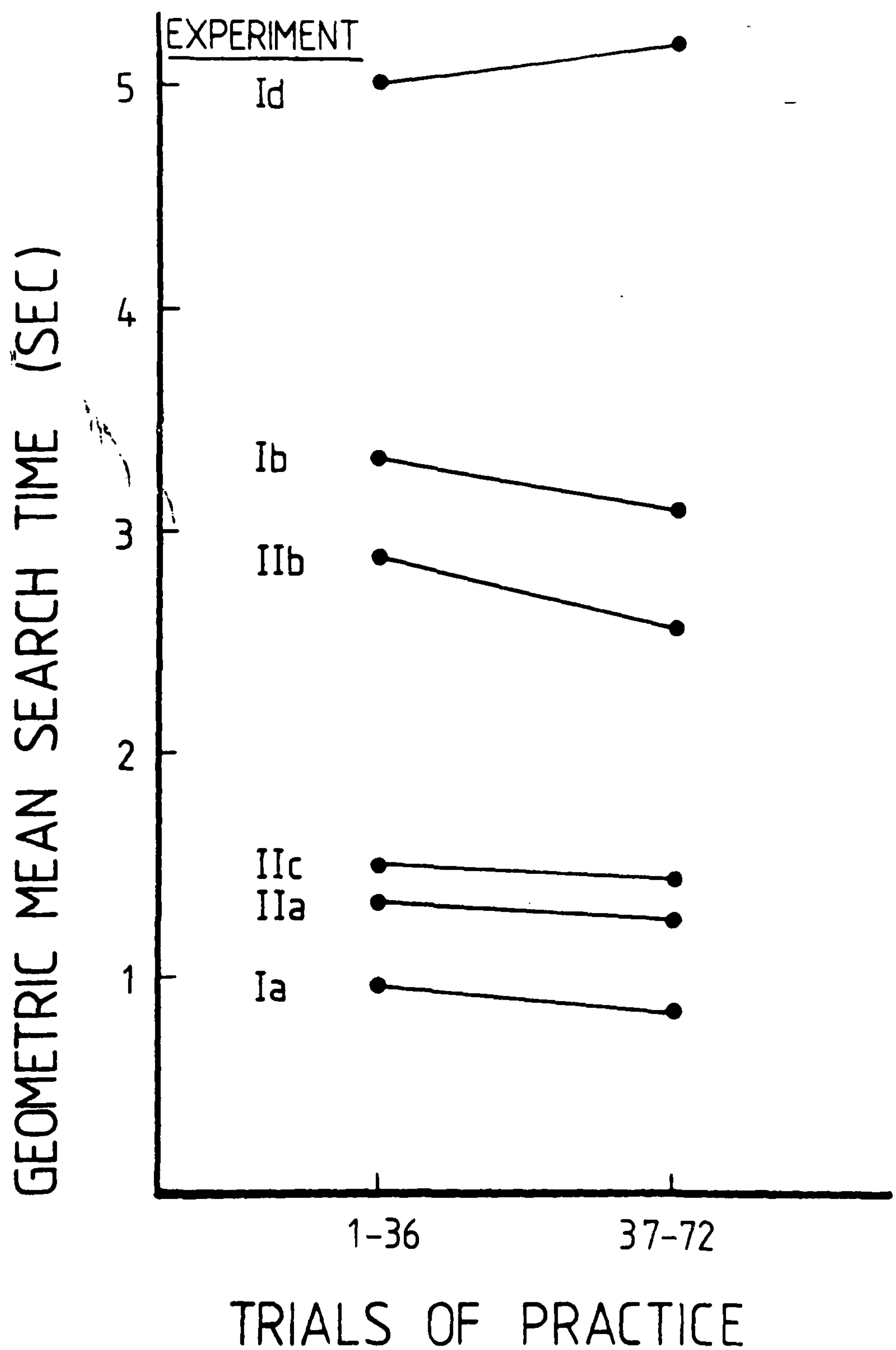

MEAN SEARCH TIME (SEC)
4,0
3,5
3,0
6
12
18
24
30
36
42
48
54
60
66
72
TRIALS OF SEARCH PRACTICE

Figure 7. Geometric Mean Search Time Versus Trials of Practice for First and Second Halves of Six Experiments.


EXPERIMENT
Id
Ib
IIb
IIc
IIa
Ia
5
4
3
2
1
GEOMETRIC MEAN SEARCH TIME (SEC)
1-36
37-72
TRIALS OF PRACTICE

experiments. This is probably due to fatigue developing during the sessions for Experiment Id, which lasted slightly longer (due to larger average search times) than sessions for other experiments. The greatest improvement between halves of the experiment was associated with high similarity of target and background colors. Perhaps, subjects learned to make the difficult discrimination between target and background more accurately during the 72 trials of this experiment. None of the six trends in Figure 7 is statistically significant.

The effects of practice in this research were small by any standard. The relative insignificance of experience in a search task was also noted by Enoch (cited by Boynton, 1960) who found that experienced photointerpreters do not exhibit better performance or different eye movements in a search task than do untrained observers. More recently, Shiffrin and Schneider (1977) have offered a theory of human information processing which predicts little improvement of search performance when the defining characteristics of the target on one trial are shared by nontargets on other trials. The targets' characteristics (digits and colors) were often shared by nontargets in other trials of this research, so a practice effect should not be expected, according to Shiffrin and Schneider.

CHAPTER 11

EVALUATION OF WILLIAMS' EQUATION FOR PREDICTING SEARCH TIME

Search time has been the dependent variable throughout this research because it is an easily measured yet highly representative aspect of search performance. Search time also is a variable of great interest in practical tasks involving search. Clearly, it would be desirable to be able to predict search time for targets on displays of given characteristics. Williams (1967a) has developed a formula for such predictions, which is based on the model of search presented in Williams (1966b). The formula is:

$$t_{median} = \frac{\sum^{N} S_i}{2R} + D$$

where t is the search time, N is display density, R is the average fixation rate (about 3 per second for alpha-numerics), D is a delay which is characteristic of the difficulty of the search (generally between 0.5 and 1.5 seconds), and the factor of 2 in the denominator reflects the fact that the target will be found after half the potential targets are searched, on the average. S_i is the normalized frequency of looking at color_i when the target is known to be of another color. The normalizing coefficient for S_i is the reciprocal of the frequency of looking at the target color. The fraction on the right of the equals sign represents the time spent on fixations, and

D represents time spent orienting to the display before the search begins, and formulating a response at the end of the search.

In order to show the predicted effects of TCS (the number of items of the same color as the target) and background items, the sum over all items (N) in Williams' equation will be broken into components corresponding to TCS and background items. Note that N = TCS + the number of background items. Hence,

$$t_{median} = \frac{1}{2R}\left[\sum^{TCS} S_i + \sum^{background} S_i\right] + D$$

However, S_i is 1 for all items of the same color as the target. Furthermore, S_i will be the same for all n_i items of nontarget color (NTC) i. Therefore:

$$t_{median} = \frac{1}{2R}\left[TCS + \sum_{i=1}^{NTC} n_i S_i\right] + D$$

This reformulation of Williams' equation would predict search times proportional to TCS when the background objects are of a color which is dissimilar to the target color ($S_i = 0$). This is because subjects rarely look at objects of the wrong color if the target color is conspicuous (Williams, 1966a, 1967b). However, several authors have demonstrated that the proportional relationship between TCS and search time is only approximate (Cahill & Carter, 1976; Green & Anderson, 1956; Smith, 1962, 1963). In terms of Williams' model, search times are predicted to increase beyond strict linearity with TCS in proportion to the number of background items and to the extent

that background objects are similar to the target ($S_i \neq 0$). The purpose of this chapter is to present evidence of this accuracy of the equation for predicting median search time.

The relation between TCS and median search time is shown in Table 18 and Figure 8. These points are medians calculated from the data of previous experiments. The relation does not appear to be linear as the equation predicts. In fact, a pair of second-order equations (one for each display density) provides a significant improvement in prediction of the points in Figure 8, compared with a pair of lines ($F(2,4) = 11.08$, $p < 0.05$). This is not to say that the relation between TCS and median search time is quadratic. Rather, the relation is unlikely to be linear, although its exact form is not known. In general, then, Williams' equation does not accurately predict the effect of the number of items of the target color (TCS). However, the equation does correctly indicate that TCS has a powerful effect on search time.

Next, we will examine the accuracy of the equation's predictions about the effects of items not of the target color, background items. In order to do this, the effect of TCS was forced to be linear by admitting only two levels of TCS in the data. Median search times were calculated for 72 displays for TCS = 1 and TCS = 10. Eighteen subjects had searched each of these 144 displays. These subjects were divided into two groups of nine at random for each display. Two medians, each based on nine subjects' search times, were calculated for each display. Hence, there were 288 medians, corresponding to searches made on 144 displays. The 144 degrees of freedom for the

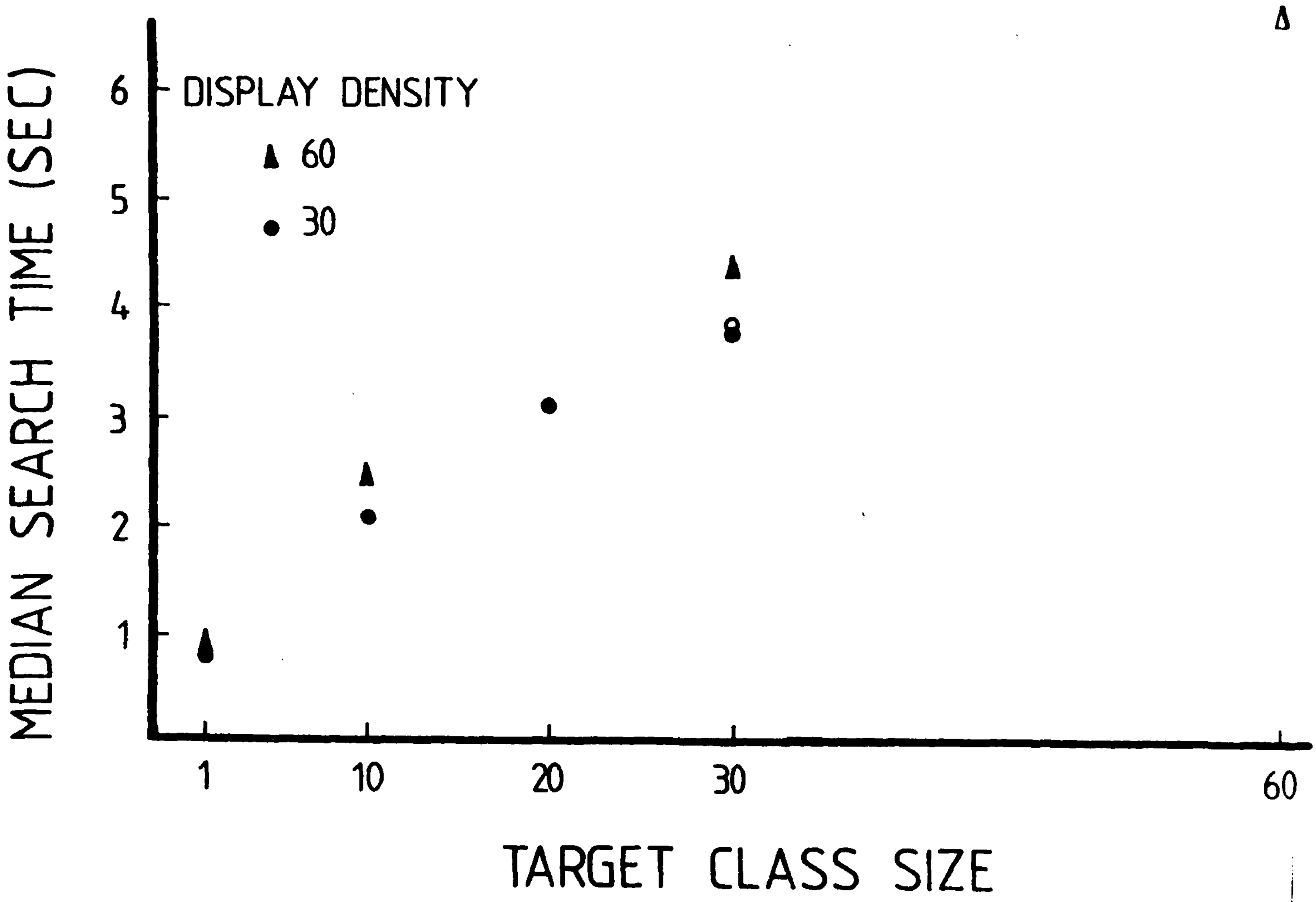
Table 18

Effects of TCS and Density on Median Search Time

	Display Density	
Target Class Size	30	60
1	0.80[a]	0.82
10	2.08	2.41
20	3.09	
30	3.80	4.33
Black and White	3.84	6.60

[a]Median search time in seconds (N = 648).

Figure 8. Median Search Time Versus Target Class Size.


DISPLAY DENSITY
60
30
MEDIAN SEARCH TIME (SEC)
1
2
3
4
5
6
1
10
20
30
60
TARGET CLASS SIZE

two medians on each display were used to calculate a mean square for pure error (Draper & Smith, 1966) which was used to test the goodness-of-fit of Williams' equation to the data.

Note that Williams' equation is easily cast in the form of a linear regression problem:

$$t_{median} = b_o + \sum_{i=1}^{NTC} b_i n_i + (b_{NTC+1}) \; TCS$$

where NTC is the number of nontarget colors and n_i is the number of items coded in each of these colors. In order to represent all possible pairs of target colors and nontarget colors, 11 coefficients were needed in the regression equation. The constant delay, D, is estimated by b_o, and the coefficients on TCS estimates 1/2R. The other coefficients represent $S_i/2R$ for all pairs of target colors and nontarget colors used in the experiments. The target color and the number of items of each of the background colors were chosen at random for each display, so the n_i were not expected to be correlated.

The analysis of variance for the regression equation is shown in Table 19. Williams' model is statistically significant, and it explains 76 percent of the variance of median search times. The model was also tested for the improvement it provided over a model which included TCS but not the terms for items not of the target's color. These terms make a statistically significant contribution to the accuracy of the model ($\underline{F}(10,276) = 3.86$, $\underline{p} < 0.01$). However, Table 19 indicates that there is a considerable lack of fit between

Table 19

Analysis of Variance for Williams' Model (TCS = 10 and 1)

Source	*df*	*SS*	*MS*	*F*	*p*
Total	287	203.230			
Regression	11	155.308	14.119	81.14	.0001
Residual	276	47.923	0.174		
Lack of Fit	132	33.728	0.256	2.59	.01
Pure Error	144	14.256	0.099		

Williams' model and the data. Perusal of the residuals does not suggest the source(s) of the lack of fit. It is certain that the fit would have been even poorer if more than two levels of TCS had been represented in the data. This is because the model predicts that median search times will be proportional to TCS, but as discussed earlier, they are not.

Overall, Williams' model is an excellent general description of how search times are affected by display characteristics. The model considers three important parameters: TCS, the number of background items, and the similarity of the background and target class items. The terms dealing with the background items improve the model significantly, compared with a model which considers TCS alone. (The minimum CIELUV color difference between targets and background items was 63.7 units. See Chapter 5.) There is evidence, though, that the form of Williams' model is somewhat incorrect. Apparently, the relationships among median search time, TCS, and background characteristics are not exactly as the equation predicts them to be.

CHAPTER 12

DISTRIBUTION OF SEARCH TIMES

The most complete statement that can be made about search time data is their Cumulative Distribution Function (CDF). The CDF is the probability of finding the target within any particular duration after a search has begun. The value of the CDF is zero at the first instant of the search, and it rises virtually to 1 at some time which is ample for finding the target in almost all attempts. A statement of the CDF also specifies the median, mean, variance, skewness, and all other moments of the search time data.

Among the first investigators to discuss their search time data in terms of a CDF were Krendel and Wodinsky (1960). They assumed that the probability of finding the target is constant for all fixations of the eyes during a search. They also assumed that the probability of finding a target during a fixation does not depend on events during other fixations. These statements are represented formally as a geometric CDF, or as an exponential CDF if the duration of the fixations is considered to be negligible compared with the search time. The equation for the exponential CDF is:

$$CDF = 1 - e^{-at}$$

The mean of this distribution is the reciprocal of a, and the variance is the square of the mean. Krendel and Wodinsky (1960) provided convincing evidence of the general adequacy of their model. Other investigators also found that search times are described well by an exponential distribution, although they offer differing interpretations of the exponent, "a" (Bloomfield, 1972; Engel, 1977; Williams, 1966b). Bloomfield (1972) suggested that the exponential model would be improved if the variable t were adjusted to $(t-t_r)$ where t_r represents response time. He showed that t_r changes with some characteristics of the search displays. Engel (1977) used a constant value of 0.2 second for t_r when fitting an exponential model to his data.

The exponential model is appealing due to its theoretical simplicity and its empirical support. However, Krendel and Wodinsky (1960) sometimes found statistically significant departures of their data from exponential form. Bloomfield (1972) noted that an exponential model was least adequate to fit his data when there was high similarity between the (size coded) targets and the background items. This finding suggested that the exponential model would fit data from the present research to the extent that the target and background colors were dissimilar.

An alternative to the exponential model was discussed by Engel. He noted that the process assumed to generate an exponential (or geometric) CDF includes sampling with replacement. In other words, search time would be expected to have an exponential CDF if subjects are as likely to look at an item that has already been inspected as

they are to look at a new item. If other assumptions are kept the same and the search sampling is made without replacement, then the CDF would rise linearly with time. These two types of CDF, then, represent two extreme models of man as a searcher. The exponential model implies that the searcher is memoryless, and the linear model implies a searcher who knows exactly where he has already looked and avoids repeated fixations on the same item. Engel found that his data were best described by the exponential model.

A third model of search times is often assumed for purposes of statistical analysis, the normal CDF. These three models: exponential, linear, and normal were compared for fit with data from this research. Seventeen sets of 648 search times which were each generated under uniform conditions of TCS, number of background items, and target-background color difference were selected for this comparison.

The empirical CDF for each set of search times was calculated by putting the search times in order and pairing with each search time the proportion of all search times in the set which was less than or equal to that search time. For example, the largest search time in a set was paired with the value 1.0 because 100% of the search times were of that magnitude or less.

Each of the model CDF's, which were to be compared with an empirical CDF, have some unspecified parameters which were chosen on the basis of the data. For example, the mean and variance of the normal CDF were estimated in the usual way. The equation of the linear CDF is:

$$CDF = b\ (t - t_r)$$

The parameters "b" (fixation rate) and t_r (response time) can be estimated by least squares, using the form:

$$CDF = b(0) + b(1)\ t$$

where b(1) stands for b, and t_r is estimated by -b(0)/b(1). Similarly, the parameters of the exponential CDF:

$$CDF = 1 - e^{a(t-t_r)}$$

may be estimated using log least squares:

$$\ln\ (1 - CDF) = b(0) + b(1)\ t$$

where b(1) stands for a, and t_r is estimated by -b(0)/b(1). CDF models were generated by using these log least squares estimates. Experience with these models of the exponential CDF indicated that they are poor for several reasons. For example, -b(0)/b(1) is a poor estimate of response time because it sometimes had a negative value, which can have no meaningful interpretation because response time cannot be negative. Furthermore, using -b(0)/b(1) to estimate response time produced a model which predicted negative values of the CDF when the observed search time is less than -b(0)/b(1). CDF can only have positive values because CDF is a probability, and

probabilities are, by definition, constrained to be less than one and greater than zero. Because of these shortcomings of -b(0)/b(1) as an estimate of response time, an alternative estimate, suggested by Bloomfield (1973) was tried. He estimated response time by the minimum search time observed in a set of search data. This estimate has none of the drawbacks of -b(0)/b(1) because it can never be negative, and there are never any observed search times less than the minimum search time. Bloomfield's method of estimating response time is also considered to be preferable to that used by Engel (1977) who chose an arbitrary value (0.2 second) to represent response time under all search conditions.

The log least squares estimates of the exponent of the exponential CDF were not least squares estimates. Consequently, the error variance of models estimated by log least squares was inflated, compared with models estimated by a least squares method. This inflation was quite substantial. Compared with least squares estimates to be discussed later, the log least squares estimates produced error variances which were at least an order of magnitude larger for each of the 17 data sets modeled.

Nonlinear regression (Jennrich, 1977) is a method which seeks to estimate parameters so as to minimize the residual sum of squares, given the form of the function being estimated (the exponential CDF in this case), the partial derivatives of this function with respect to the parameters to be estimated, and initial estimates of the parameters. Hence, when it performs as intended, nonlinear regression estimates are least squares estimates because they make the error

variance of a model as small as possible. Nonlinear regression was used to estimate the exponent and the response time of the exponential CDF, using the log least squares estimate of the exponent and the minimum search time as initial estimates of the exponent and response time.

The nonlinear estimates of the response time were constrained to be greater than zero and less than or equal to the minimum search time in each data set. The nonlinear regression estimates of the response times, shown in column 8 of Table 20, invariably converged to the upper limit. Hence, the minimum search time estimate of response time, suggested by Bloomfield (1973), was also the estimate chosen by nonlinear regression. Column 9 of Table 20, headed $F(1,646)$, lists tests of the extra sum of squares (Draper & Smith, 1966) for the contribution of the response-time parameter to the precision of the exponential model of search time. Response time appears to contribute a great deal to the quality of the model under all search conditions considered.

Bloomfield (1972) states that response time increases as the similarity increases between the target and nontargets. The data from Experiment II should be directly relevant to this assertion because the similarity of the target and nontarget (background) colors was varied while other display conditions were held constant. Response times, estimated by the minimum search times under each of six experimental conditions, are listed in Table 21. The response time tends to increase as the background color becomes similar to the target color. Hence, Bloomfield's (1972) claim, which was made in

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Table 20

Statistics on the Cumulative Distributions of Search Times

Search Conditions[a]			Correlations[b] ($\times 10^2$)						
TCS	DE	NOB	Linear	Normal	Exponential	Exponent	Response Time (sec)	$\underline{F}(1,646)$ for Response Time	$\underline{MS}_e$ ($\times 10^3$)
60		0	64	72	99.8	- .117228	.80	3,409.45*	.2938653
30		0	54	62	99	- .226082	.63	2,913.36*	.8329956
30		0	77	83	99	- .257031	.54	2,252.54*	1.1682573
30		0	76	87	99	- .237149	.74	2,249.09*	1.5196763
30	228	29	80	85	99.5	- .253499	.68	3,704.90*	.8313672
30	161[c]	30	76	81	98	- .196841	.68	1,126.16*	2.5955020
30	12	29	78	85	99.6	- .201343	.76	3,665.20*	.6797160
10	161[c]	20	55	90	95	- .471458	.52	867.39*	7.8562500
10	161[c]	50	51	82	97	- .396064	.54	996.93*	5.7003535
1		0	94	97	88	-3.061920	.26	950.79*	18.5264908
1	228	29	88	93	86	-3.249040	.38	1,014.18*	21.0139975
1	228	59	94	98	84	-2.437590	.20	499.86*	24.1439119
1	161[c]	29	64	68	89	-1.132730	.21	395.97*	16.7116486
1	161[c]	59	64	75	93	-1.231250	.28	755.82*	11.5238838
1	36	59	88	93	91	-2.316220	.29	1,053.37*	15.0161162
1	12	29	80	85	99	- .662628	.62	3,872.48*	2.4081175
1	12	59	67	74	99	- .495811	.51	4,829.20*	.8522526

Table 20 (Continued)

[a]TCS is Target Class Size, NOB is the number of background items (not of the target class), DE is the target-background color difference (CIELUV).

[b]$\underline{N} = 648$.

[c]Average color difference in a five-color code.

* $\underline{p} < .05$

Table 21

Estimated Response Time and Target-Background Color Similarity

Search Condition		Color Similarity	
TCS	NOB[a]	High	Low
30	29	0.76[b]	0.67
1	29	0.62	0.38
1	59	0.51	0.20

[a]Number of background items.

[b]Estimated response time in seconds.

the context of size similarity, seems also to be valid for color similarity: response time increases as target-background similarity increases.

Columns 4, 5, and 6 of Table 20 display correlations of the observed CDF of search times with each of three models of the CDF: linear, normal, and exponential (estimated by nonlinear regression). The exponential model was superior to the others in almost all conditions. The normal model was better when practically no search was required because the target stood alone in the field of view (TCS = 1 and NOB = 0 in columns 1 and 3 of Table 20) or other items in the field of view were quite dissimilar to the target (DE was large, as compared with other values in column 2 of Table 20). The linear model was generally inferior to the exponential model, indicating that the memoryless property of the exponential model is more representative of search by humans than the perfect memory of past fixations implied by the linear model of the CDF. The exponents for the exponential models are listed in column 7 of Table 20.

The exponents listed in Table 20 generally become smaller as TCS increases and as the color difference between the target and background decreases. In general, the exponent becomes smaller as the search material becomes more difficult. Several interpretations of these exponents have been given by various authors. For example, Williams (1966b) derived an equation in which the exponent is proportional to the subject's scanning rate (area/time) divided by the total area of the display. (The proportionality constant is the logarithm of the probability of not finding the target during a

single scan of the display.) The decreasing exponent associated with increasing TCS or target-background similarity in the present research would indicate a slowed scanning rate, according to Williams (1966b). Mackworth (1976) has observed that scanning rate decreases as the search material becomes more difficult, so these results are in agreement with Williams' (1966b) interpretation of the exponent and Mackworth's (1976) observation. Williams (1966b) proposes that the scanning rate be used as a measure of the target's "conspicuity," or conspicuousness.

Engel (1977) assumes that the scanning rate is constant, and that the area perceived during a search fixation changes with the difficulty of the search material. He offers convincing evidence of shrinkage of the "conspicuity area" as the similarity of the target and background increases. The conspicuity area is the region around the line of sight (approximately a disc) within which the probability that the subject will recognize the target during a single glance is at least 0.5. The radius of the conspicuity area is related by a complicated formula to the exponent of the exponential model of the search time CDF. The range of exponents listed in Table 20 corresponds to conspicuity areas with radii varying from about 1.3° to 27° of visual angle. Qualitatively, the conspicuity area enlarges as the magnitude of the exponent becomes larger. This effect is also discussed by Mackworth (1976) who claims that slow scanning and narrowed attention is the way the visual system responds to difficult search material.

The error mean square for the exponential model, shown in the last column of Table 20, is generally quite small relative to the scale of the CDF (0 to 1), indicating that the exponential model may be sufficiently accurate for some applications. The model is least accurate when the task least requires search (i.e., when the target is immediately obvious to the observer because it stands alone in the field of view or because other items in the field of view are unlike the target).

The error mean square summarizes the size of the deviations of the observed CDF from the model CDF. The pattern of these deviations gives an indication of the ways in which the model fails to represent the observations. There was a consistent pattern of deviations of the exponential model from the observed search times in this research. The exponential model predicted that short search times would be more likely than they actually were, and that long search times would be less likely than they actually were. (Of course, the size of these deviations was very small under most conditions studied.) This pattern resulted because the observed search times had a sigmoid character with a positive acceleration for short search times and a negative acceleration for long search times. In contrast, the exponential model has a negative acceleration for all values of search time. In order to minimize the error sum of squares, the model must overshoot the observations for short search times and undershoot the observations for long search times. This pattern of deviations of the model from the data indicates that the true distribution of search times may not be exponential, although the exponential model

is a very good approximation, at least when the subject must search for the target in order to find it.

To summarize, the exponential model of the Cumulative Distribution Function (CDF) of search times has been found to be a good approximation to observed search times. The exponential model which is based on a prototype of "memoryless" searching seems to fit the data better than a linear model which assumes, in contrast to the exponential model, that search is conducted without redundant fixations. The exponential model is also superior to the normal distribution as a description of the CDF of search times, except when the target is immediately obvious and no search is required. However, the exponential model deviates from the general sigmoid shape of the CDF of observed search times.

A parameter representing response time was shown to improve the accuracy of the exponential model. A nonlinear regression estimate of the exponent is interpretable in terms of Williams' (1966b), Engel's (1977), and Mackworth's (1976) theories of the distributions of search times. The interpretations include slowed scanning and narrowed attention when the search material becomes difficult. In this research, difficulty increased (and the exponent decreased in magnitude) as the Target Class Size increased or as the color difference decreased between the target and background items.

CHAPTER 13

GENERAL SUMMARY

An interlocking series of experiments was conducted to investigate visual search with color. The experiments dealt with the effects of (1) the number of items of the target's color, (2) the items not of the target's color, (3) the similarity of the target color and other colors used on the display, (4) target position, (5) items near the target, (6) the arrangement of target-colored items, (7) differences among subjects, and (8) learning by the subjects during search practice.

The initial experiment was done to show the effect of the number of items of the same color as the target. This variable was called Target Class Size (TCS). It had previously been shown that mean search time is linearly related to TCS when TCS varies from 10 to 60 on a display of density 60. However, subsequent research has suggested that this linear relation changes when TCS is smaller than 10, and that the search time versus TCS curve levels off as TCS approaches 1. Therefore, the generality of the linear relationship was tested by examining the effect of TCS as it approached unity on displays representing more than one density. A linear relation between TCS and search time would require that the times obtained for a TCS of 1 be on the trend line established with higher TCS's. If the TCS versus time curve levels off as suggested, then times

obtained for a TCS of 1 could be greater than predicted by an extension of this linear trend.

Displays were constructed with randomly dispersed three-digit numbers and a single target designated by its first two digits, which were unique on each display. These displays, which were coded with five colors, controlled display density (30 or 60 items), target position, and the number of items adjoining the target (0, 1, or 2). TCS was 1, 10, or 30 for separate groups of 18 subjects. Another group of 18 subjects searched black-and-white displays (TCS = 60 or 30 when display density is 60 or 30, respectively). Mean search times were linearly related to TCS when TCS varied from 1 to the display density. Search time was reduced by more than 90% when color coding with TCS = 1 was used on displays with density 60, compared with time to search the same displays without color.

Another result of this experiment was that displays on which density was 60 produced longer searches than displays on which the density was 30, even though TCS was the same in both cases. If items not of the target color are called background items (the number of background items, NOB, equals density minus TCS), then the prolonged search times associated with higher density must be attributed to the NOB. This is because the NOB is the only aspect of density which can be varied independently of TCS.

In order to assess more thoroughly the effect of NOB on search times, a second experiment in which NOB was an explicit variable was performed with the same displays recoded. In this experiment, TCS was either 1 or 30. NOB was 0 or 29 when TCS was 30, and NOB was

0, 29, or 59 when TCS was 1. Separate groups of 18 subjects searched displays in each NOB condition. Results confirmed the overwhelming effect of TCS found in the first experiment. There was no significant NOB X TCS interaction. Search times were completely unaffected by background items when their color was of high contrast with the target's color. However, background items produced a considerable effect when their color was "near" the color of the target in a uniform chromaticity diagram (a version of the CIE color diagram stretched so that equal distances represent equally perceptible changes of color). When the color of the background items is similar to that of the target, equal successive increments of NOB caused progressively smaller increments of search time.

The results of the second experiment suggested that color difference in a uniform color space might be a good measure of the disruptive power of items not of the target's color. A third experiment was conducted in which TCS was 1 and display density was 60. The color of the background items was controlled so that the color difference between the target and background colors had one of five values: 0 (the same color), infinite (no background items), and three intermediate color-difference values in the CIELUV uniform color space. Search time increased progressively as the color difference between the target and the background items decreased. More detailed analysis of this effect, using eye-movement data, confirmed that the color difference between the target and background items determines the conspicuousness of the target.

The preceding experiments were reanalyzed in order to determine whether the position of the target or the number of items adjoining the target affect search times. The two position variables, target placement in the upper or lower half of the display and eccentricity of the target, had no consistent effect on search time. Target placement near the outer edge of the display yielded faster searches on black-and-white displays than placement nearer the center of the display. This result is directly contradictory to results published by Baker, Morris, and Steedman (1960). The finding of significant high-order interactions of target position and other variables, and the contradictory nature of various findings for target position, imply that target position may affect search time through complex interaction with other display variables.

The number of items adjoining the target was not found to affect search time in any consistent way. A special experiment to determine whether there is an effect of color contrast of the target and its neighbors detected no such effect. As with the results for target position, the findings of significant high-order interactions and changes of effects from one experiment to another suggest that the effect of the target's neighbors may depend on other display variables.

Although the position of the target and the presence of other items adjoining the target were found to have no consistent effect, the pattern of target-colored items did affect search time. Two types of arrangements of target-class items were a random dispersion, and a sinuous pattern unified by proximity, continuity, and (color) similarity of the elements. When the target class items

were patterned, the target could be in the pattern or out of the pattern. It was found that when the target was in the pattern it was found in the same amount of time required to find a target on a random display. However, when the target was outside the pattern, it was found faster than when it was in the pattern or on a random display. This result confirmed an earlier finding by Brown and Monk (1975), and it suggested that subjects tended to search isolated target class items in preference to grouped target class items.

These experiments show the effects on search time of characteristics of the displays: TCS, NOB, similarity of the target and background colors, and arrangement of target-colored items. Characteristics of the subjects also influence search times. Indeed, one of the most consistent findings in the literature of visual search is that some people find the targets considerably faster than other people. Twelve individual difference variables suggested in the literature of visual search were studied to determine whether they are associated with differences in search time among 78 subjects. The variables studied (reading speed; smoking habits; recent drug or alcohol use; sex or age of the subject; stereo acuity; foveal acuity; parafoveal acuity at 1.7°, 2.4°, 3°, or 4°; eccentricity; and color vision) were not significantly related to search speed.

Another often assumed but little investigated phenomenon in a search task is learning. The assumption of a need for extended practice before taking search data was investigated in six experiments with 108 subjects who each searched 72 displays after having from one to four orientation trials. The 72 repeated measures for each

subject were regarded as a 72-trial learning experiment for present purposes. The 72 trials were split into two halves, the first and last 36 trials, which were matched for all display conditions (density, target position, TCS, etc.). The 36 displays in each half were assembled into six blocks of six consecutive trials. The analysis of variance, mustering power across all 108 subjects, showed that the only significant change across 72 trials of practice (about one hour) was an interaction of the particular experiment (of the six) and halves of the 72 trials. Surprisingly, there was no overall learning effect.

Finally, data from many of the preceding experiments (17 sets of 648 data) were cast in the form of a Cumulative Distribution Function (CDF) of search times. This function indicates the probability that search time will be less than any given value. The empirical CDF's obtained in this research were well fit by the theoretical exponential CDF. The fit was improved by inclusion of a term to represent response time. The theoretical interpretation of the exponential CDF is that human searching is practically memoryless, and that searchers respond to more difficult search material (large TCS or small color difference between target and background items) by slowing the rate of search and narrowing the visual area within which a target can be detected.

In summary, several display characteristics have been shown to affect search time. The number of items of the target's color (TCS) has a predominantly linear effect on search time when TCS varies from 1 to the display density. Items not of the target's color (background

items) prolong search times only to the extent that they have a color similar to the target's. Similarity of target and background colors is a function of their color difference (in a uniform color space). In contrast to results for these display characteristics, characteristics of subjects were remarkably unrelated to search speed. For instance, it is surprising that practice for an hour on a search task has no consistent effect on search times. Furthermore, the best predictors of individual differences in search speed are practically unrelated to mean search times of the subjects. These two findings indicate that individual differences in search speed is a topic requiring further research.

FOOTNOTES

[1]There is evidence that even color coding will not improve search performance if there are too few items on the display. Christ (1975) and Christ and Corso (1975) found that the advantage of color (over other codes) decreases as display density decreases. Cahill and Carter (1976) showed that search times are not diminished by color coding unless there are more than about 20 items on the display.

[2]Roscoe Laboratories, Inc., 36 Bush Avenue, Port Chester, N.Y. 10573.

[3]All luminance measurements were made with a "Spectra" brightness spot meter manufactured by Photo Research Corporation, 38 Cahuenga Blvd., Hollywood, Calif.

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APPENDIX A

STANDARD INSTRUCTIONS TO SUBJECTS

"You will be looking for targets on this circular display screen. [Experimenter points to the screen.] The targets will be three-digit numbers like this [points to an example], and there will be many such numbers on the display. All numbers will be oriented horizontally. I will tell you the first two digits of the target number; no other number on the display will start with those two digits. I will also tell you the color of the target three-digit number. Knowing the target's color may help you to find the target because you need not bother looking at numbers of the wrong color.

You will set the pace of the experiment because you control presentation of the search displays. After I have told you the first two digits and the color of the next target, you may press this button [points to the push button] whenever you are ready to search for the target. The display will be visible as long as you push the button, and will disappear when you release the button. Release the button when you have found the target and have noted its third digit. I am assuming that the amount of time you press the button represents the amount of time you took to find the target and note its third digit, so please don't release the button before noting the third digit, and do not unnecessarily delay releasing the button after noting the third digit.

After releasing the button, please tell me the third digit. You can take as much time as you like before reporting that digit because I won't be recording that time. Letting up on the button as soon as possible is the thing to concentrate on. Overall, you are to search as rapidly as possible without making <u>any</u> mistakes in saying the third digit of the target."

APPENDIX B

COLOR SPECIFICATIONS

Color # (Roscolene)[a]	Color Name[b]	CIE Tristimulus Values[c]			Luminance (mL)	Color Difference (CIELUV)					
		X	Y	Z		7	6	5	4	3	2
1 (874)	Green	3.01	13.27	1.72	0.37	219	36.4	228	146	260	96.3
2 (851)	Greenish Blue	10.87	15.41	27.76	1.51	167	110	175	146	225	
3 (823)	Red	22.52	8.84	0.01	1.45	66.7	262	63.7	138		
4 (807)	Yellow	75.31	72.21	2.75	4.09	122	135	128			
5 (838)	Ligh Purplish Red	28.75	12.27	14.83	1.72	11.8	232				
6[d] (878)	Yellowish Green	27.64	52.83	8.83	2.15	224					
7[d] (837)	Dark Purplish Red	22.33	8.54	10.75	1.48						

[a] See Note 2.

[b] Suggested color designations for self-luminous sources (Kelly, 1943).

[c] Coordinates are based on the luminous source used in this research.

[d] These colors were used only in Experiments II and III.

APPENDIX C

CORRELATIONS[a] OF SEARCH TIME AND PERSONAL CHARACTERISTICS OF 78 SUBJECTS

Variable	13	12	11	10	9	8	7	6	5	4	3	2
1. Mean Search Time (Z Score)	-16	- 9	9	21	8	4	- 4	-19	- 6	-11	-5	14
2. Sex	-22*	- 5	- 5	3	-14	-19	2	16	- 2	- 8	2	
3. Smoking	9	- 4	- 7	5	- 2	6	- 1	8	- 2	27*		
4. Age	4	- 6	- 2	13	6	4	- 5	24*	19			
5. Drug/Alcohol (24 hr)	- 4	4	- 4	- 2	- 4	- 4	- 8	7				
6. Acuity 0°	- 9	31*	- 9	7	- 4	4	-20					
7. Acuity 1.7°	- 2	-45*	- 2	22*	52*	40*						
8. Acuity 2.4°	- 3	-14	-23*	33*	50*							
9. Acuity 3.0°	-14	-29*	-14	55*								
10. Acuity 4.0°	-14	-11	8									
11. Reading Speed	- 3	14										
12. Stereo Acuity	-10											
13. Color Vision												

[a]Multiplied by 100.

* $\underline{p} < .05$ (two-tailed test)